References

Adler, R. J., G. F. Kiuttu, B. E. Simpkins, D. J. Sullivan and D. E. Voss, "Improved electron emission by use of a cloth fiber cathode", *Rev. Sci. Instrum.*, vol. 56, no. 5, pp. 766–767, May 1985.

Agee, F. J. S.E. Calico, K.J. Hendricks, M.D. Haworth, , T. Spencer,D. Ralph, E. Blankenship, M.C. Clark and R.W. Lemke, Pulse-Shortening in the Magnetically Insulated Line Oscillator, *Intense Microwave Pulses IV,* pp.144-152,1996.

Ashby, D. ETF., J. W. Eastwood, J. Allen, K. C. Hawkins, and L. M. Lea , "Comparison between Experiment and Computer Modeling for Simple MILO Configurations," *IEEE Trans. Plasma Sci.,* Vol. 23, pp. 959-969, 1995.

Barker, R. J., E. Schamiloglu, High power microwave sources and technologies, IEEE Press Series on RF and Microwave Technology, 2001.

Barker, R.J., E. Schamiloglu, *High power microwave sources and technologies,* IEEE Press Series on RF and Microwave Technology, 2001.

Barker, R.J and E. Schamiloglu, "High Power Microwave Sources and Technologies," *IEEE Press*, *New York*, 2001.

Basu, B. N., *Electromagnetic theory and applications in beam-wave electronics, Singapore, World Scientific,* 1996.

Bekefi, G., and T.J. Orzechowski, "Giant microwave bursts emission from field emission, relativistic-electron-beam magnetron," *Phys. Rev. Lett*., vol. 37, 379, 1976.

Benford, J., and G. Benford, "Survey of pulse shortening in high power microwave sources," *IEEE Trans. Plasma Sci.,* Vol. 25, pp. 311-317, 1998.

Benford, J., D. Price, H. Sze and D. Bromley, "Interaction of a vircator microwave generator with an enclosing resonant cavity", *J. Appl. Phys.*, vol. 61, pp. 2098–2100, March 1987.

Benford, J., D. Price, and W. DeHope, "Lowered plasma velocity with Cesium Iodide/Carbon Fiber Cathodes at high electric fields," *Conference Record 25th IEEE International conference on Plasma Science, Raleigh,* NC, Vol. 2, pp. 695-698, 1998.

Benford, J., J. A. Swegle, and E. Schamiloglu, High power microwaves, CRC Press, 2016.

Benford, J., V. L. Granatstein, and I. Alexeff, “Relativistic magnetron,” High Power Microwave Sources, Eds. Boston, MA: Artech House, pp. 351-395, 1987 .

Bergeron, K. D., “One- and two-species equilibria for magnetic insulation in coaxial geometry,” *Phys. Fluids,* Vol. 20, pp. 688-697, 1977.

Birge, B., “ PSOt, A Particle Swarm Optimization Toolbox for Matlab” , *IEEE Swarm Intelligence Symposium Proceedings,* April 24-26, 2003

Black, W. M., S.H. Gold, A. W.Fliflet, D.A. Kirkpatrick, W.M.Manheimer, R.C.Lee, V.L. Granatstein, D.L Hardesty, A.K Kinkead, and M. Sucy, “Megavolt, multikiloamp Ka-band gyrotron oscillator experiment,” *Phys. Fluids B*, vol. 2, no.1, pp. 193-198, Jan., 1990.

Bluhm, H, "Book on Pulsed Power Systems", Springer- 2006

Bogdankevich, L. S., M. V. Kuzelev, and A. A. Rukhadze, "Plasma microwave electronics," *Soviet Phys. Uspekhi,* Vol. 24, pp. 1, 1981.

Bratman, V. L., G. G. Denisov, M. M. Ofitserov, S. D. Korovin, S. D. Polevin, and V. V. Rostov, “Millimeter- wave HF relativistic electron oscillators,” *IEEE Trans. Plasma Sci.*, Vol. 15, pp. 2-15, 1987.

Burkhart, S., “Multigigawatt microwave generation by use of a virtual cathode oscillator driven by a 1–2 MV electron beam”, *J. Appl. Phys.*, vol. 62, pp. 75–78, July 1987.

Calico, S. E., F. J. Agee, M. C. Clark, R. W. Lemke, and M. C. Scott, “Rep-Rate Operation of a Magnetically Insulated Line Oscillator (MILO),” *Proceeding 1st International Workshop on Crossed Field Devices, Ann Arbor,* MI, pp. 15-16, 1995.

Calico, S. E., M. C. Clark, and M. C. Scott, “Experimental results of a high power rep-rate velvet cathode,” *IEEE Pulsed Power Conference Kirtland AFB, Albuquerque, NM*, Vol. 1, pp. 677-681, 1995.

Calico, S. E., M. C. Clark, R. W. Lemke, and M. C. Scott, “Experimental and Theoretical investigation of magnetically insulated line oscillator (MILO),” *Intense Microwave Pulses, Proc. SPIE 2557, H. E. Brandt Ed*., pp. 50-59, 1995.

Caryotakis,G, “The klystron: a microwave source of surprising range and endurance,” *Phys. Plasmas*, vol. 5, no. 5, pp. 1590-1598, May, 1998.

Carter, R.G., “Accuracy of Microwave Cavity Perturbation Measurements” , *IEEE transactions on microwave theory and techniques*, vol. 49, No. 5, pp. 918-913,May 2001.

Chen, D.B., Z. K. Fan, H. J. Zhou, F. Q. Gao, H. He, Y. H. Guo, D. Wang, X. D. Wang, H. T. Gong, and H. S. An, “L-Band Hard-tube Magnetically Insulated Oscillator,” high power laser part. beams, vol. 19, no. 8, pp. 1352–1356, 2007.

Chen, D.B., Z. K. Fan, Z. W. Dong, Z. Xu, H. J. Zhou, Y. H. Guo, H. He, H. T. Gong, and H. S. An, “Experimental study on Ladder Cathode L-band MILO,” High power laser part. beams, vol. 19, no. 5, pp. 820–824, 2007.

Chen, Dai-Bing, D. Wang, Fan-Bao Meng, and Zhi-Kai Fan, “Bifrequency magnetically insulated transmission line oscillator,” *IEEE Trans. Plasma Sci*., Vol. 37, pp. 23-29, 2009.

Chen, Dai-Bing, D. Wang, Fan-Bao Meng, Zhi-Kai Fan, F. Qin, and J. Wen, “ Bifrequency HPM generation in a MILO with azimuthal partition,” *IEEE Trans. Plasma Sci.,* Vol. 37, pp. 1916-1920, 2009.

Chen, H. C., “General Theory of the Diocotron Instability of a Relativistic Electron Beam,” *IEEE Trans. Nuclear Sci.,* Vol. 32, pp. 2380-2382, 1985.

Chodorow, M, E.L. Ginzton, I. R. Neilsen, and S. Sonkin, “Design and performance of high-power klystrons,” *Proc. IRE*, vol. 41, p. 1584, 1953.

Chu, K. R., “The electron cyclotron maser,” *Rev. Mod. Phys.,* Vol. 2, pp. 489, 2004.

Clark, M. C., B. M. Marder, L. D. Bacon, “Magnetically insulated transmission line oscillator,” *Appl. Phys. Lett.,* Vol. 52, pp. 78-80, 1988.

Collins, R.E., “*Foundation for Microwave Engineering,”* New York: McGraw-Hill, 1988.

Corana, A., M. Marchesi , C. Martini and S. Ridella , “Minimizing Multimodal Functions of Continuous Variables with the ‘Simulated Annealing’ Algorithm,” *ACM Transactions on Mathematical Software*, vol.13, pp.262-80,1987.

Cousin, R., “Understanding of mechanism of high frequency devices as MILO type,” Ph.D. Thesis, Ecole Polytechnique, France, 2005.

Cousin, R., J. Larour, J. Gardelle, and B. Cassary, “Evidence of the 3π/4 interaction mode in a compact magnetically insulated line oscillator process,” *J. App. Phys.,* Vol. 35, pp. 084512, 2006.

Cousin, R., J. Larour, P. Raymond, and A.J. Durand, “Theoretical and experimental behavior of a compact magnetically insulated line oscillator electromagnetic structure,” *Review of Scientific instruments,* vol. 76, pp.124701(1)-(8), 2005.

Cousin,R., J. Larour, J. Gardelle, B. Cassany, P. Modin, P. Gouard, and P. Raymond, “Gigawatt emission from a 2.4-GHz compact magnetically insulated line oscillator (MILO),” *IEEE Trans. Plasma Sci*., vol. 35, no. 5, pp. 1467–1474, Oct. 2007.

Creedon, J. M., “Relativistic Brillouin flow in the high ν/γ diode,” *J. Appl. Phys.,* Vol. 46, pp. 2946-2955, 1975.

Creedon, J.M., “Relativistic Brillouin flow in the high V/γ diode,” *Journal of Appl. Phys.* Vol.46, 1975.

DiCapua, M. D., “ Magnetic Insulation,” *IEEE Trans. Plasma Sci.* vol. 11, pp. 205-215, 1983.

Dong, W., Fen Qin, Chen Dai-Bing and Zhi-Kai Fan, “Magnetically insulated transmission line oscillator oscillated in a modified HEM11 mode,” Chin,Phys.Soc.,Vol.18, No.10, Oct.2009.

Dorsey, R. E., J.D. Johnson and W.J. Mayer , “A Genetic Algorithm for the Training of Feed forward Neural Networks,” *Advances in Artificial Intelligence in Economics, Finance and Management* (J. D. Johnson and A. B. Whinston, eds., 93-111). Vol. 1. Greenwich, CT: JAI Press Inc., 1994.

Dorsey, R. E., and W.J. Mayer , “Genetic Algorithms for Estimation Problems with Multiple Optima, Non-Differentiability, and other Irregular Features,” *Journal of Business and Economic Statistics*, 13(1), pp.53-66,1995.

Dwivedi, S., “Studies on RF behaviour of MILO,” Ph. D thesis ,IIT(BHU)*,* India, 2012.

Dwivedi, S., and P. K. Jain, “ Design Expressions for Magnetically Insulated Line Oscillator,” *IEEE Trans. Plasma Sci.,* Vol. 41, pp. 1549-1556, 2013

Dwivedi, S., and P. K. Jain, “Beam-wave interaction analysis of a magnetically insulated line oscillator,” *Phys. plasmas*, Vol. 19, pp. 082110, 2012.

Dwivedi, S., and P. K. Jain, “Electromagnetic analysis of a disk-loaded coaxial waveguiding structure for MILO,”*IEEE Trans. Plasma Sci.,* Vol. 40, no. 4, pp. 1032-1041, 2012.

Dwivedi, S., and P. K. Jain, “Magnetically Insulated Line Oscillator Performance Study and its Parameter Optimization,” *IEEE Trans. Plasma Sci.,* Vol. 41, pp. 2532-2538, 2013.

Eastwood, J. W., “Magnetically Insulated Line Oscillator Microwave Pulse Generator,” US Patent 6034572, 2000.

Eastwood, J. W., H. P. Hook, and H. C. Hakins, “The Tapered MILO,” *IEEE Trans. Plasma Sci.*, vol. 26, pp. 698-713, 1998.

Eberhart, R. C. and Y.Shi, “Comparison between genetic algorithms and particle swarm optimization”, *Evolutionary programming vii: proc. 7th ann. conf. on evolutionary conf.*, Springer-Verlag, Berlin, San Diego, CA., 1998.

Fan ,Y.W., H. H. Zong, Ting S and L.Z. Quang, “Investigation of an X- band magnetically insulated transmission line oscillator,” *Chinise Physics Society, and IOP publication Ltd.,* vol. 17, pp.1804-1808, 2008.

Fan Y. W., Y. Cheng-Wei, Z. Hui-Huang, T. Shu, Z. Jian-De, Y. Jian-Hua, Y. Han-Wu , Y. Wang , and L. Luo, “Experimental investigation of an improved MILO,” *IEEE Trans. Plasma Sci.,* Vol. 35, pp. 1075-1080, 2007.

Fan Y. W., Y. Cheng-Wei, Z. Hui-Huang, T. Shu, Z. Jian-De, Y. Jian-Hua, Y. Han-Wu , Y. Wang , and L. Luo, “Experimental investigation of an improved MILO,” *IEEE Trans. Plasma Sci.,* Vol. 35, pp. 1075-1080, 2007.

Fan, Y. W., H.H., Zhong, Z.Q. Li, H.W. Yang,T. Shu, and H. Shou,. “A metal-dielectric cathode,” *Journal of Applied Physics,* vol. 104, pp. 023304(1-4) 2008-1.

Fan, Y. W., Hui-Huang Zhong, Zhi-Qiang Li, Han-Wu Yang, T. Shu, H. Zhou, Cheng-Wei Yuan, J. Zhang, and L. Luo, “Analysis and improvement of an X-band magnetically insulated transmission line oscillator,” *J. Appl. Phys.,* Vol. 103, pp. 123301, 2008.

Fan, Y. W., Hui-Huang Zhong, Zhi-Qiang Li, Han-Wu Yang, T. Shu, H. Zhou, Cheng-Wei Yuan, J. Zhang, and L. Luo, “A metal-dielectric cathode,” *J. Appl. Phys.*, Vol. 104, pp. 023304, 2008.

Fan, Y. W., Hui-Huang Zhong, Zhi-Qiang Li, T. Shu, Jian-De Zhang, Jin-Liang Liu, Jian-Hua Yang, J. Zhang, Cheng-Wei Yuan, and L. Luo. , "Recent progress of the improved magnetically insulated transmission line oscillator," *Rev. Sci. Instr.*, Vol. 79, pp. 034703, 2008.

Fan, Yu. Wei, Hui-Huang Zhong, Zhi-Qiang Li, T. Shu, Han-Wu Yang, H. Zhou, Cheng-Wei Yuan, Wei-Hong Zhou, and L. Luo, "Repetition rate operation of an improved magnetically insulted transmission line oscillator," *Phys. of Plasma,* Vol. 15, pp. 083102, 2008.

Fan, Yu-Wei, Hui-Huang Zhong, Zhi-Qiang Li, T. Shu, Jian-De Zhang, J. Zhang, Xiao-Ping Zhang, Jian-Hua Yang, and Ling Luo, " A double band high power microwave source," *J. Appl. Phys.,* Vol. 102, pp. 103304, 2007.

Fan, Y. W., Hui-Huang, Zhong, T. Shu, and Zhi-Qiang Li., "Theoretical investigation of the fundamental mode frequency of the magnetically insulated transmission line oscillator," *Phys. plasma,* Vol. 15, pp. 123504, 2008.

Fan,Y.W., C. W. Yuan, H. H. Zhong, T. Shu, and L. Luo, "Simulation Investigation of an Improved MILO," IEEE trans. plasma sci., vol. 35, no. 2, pp. 379–383, apr. 2007.

Fazaelifar, M. and M. R. Fatorehchy, "Design, fabrication and test of parabolic cylinder reflector and horn for increasing the gain of Vlasov antenna", *Progress In Electromagnetics Research Letters*, Vol. 4, pp.191-203, 2008.

Fazio, M.V, W.B. Haynes, B.E. Carlsten, and R. M. Strinffield, "A 500MW, 1ms pulse length, high current relativistic klystron," *IEEE Trans. Plasma Sci*., vol. 22, no .5, pp. 740-749, Oct. 1994.

Fowler, R. H., and L. Nordheim, "Electron emission in intense electric fields", *Proc. R. Soc. A*, vol. 119, pp. 173–181, May 1928.

Friedman, M., "Emission of intense microwave radiation from an automodulated relativistic electron beam." *Appl. Phys. Lett.,* Vol. 26, pp. 366-368, 1975.

Friedman, M., "Propagation of an intense relativistic electron beam in an annular channel," *J. Appl. Phys.* Vol. 80, pp. 1263-1268, 1996.

Friedman, M., and V. Serlin, "Modulation of intense relativistic electron beam by an external microwave source," *Phys. Rev. Lett.* Vol. 55, pp. 2860, 1985.

Friedman, M., R. Fernsler, S. Slinker, R. Hubbard, and M. Lampe, "Efficient conversion of the energy of intense relativistic electron beams into RF waves." *Physical rev. lett.* Vol. 75, pp. 1214, 1995.
Friedman,M, J. Krall, Y.Y. Lau, and V. Serlin, "Efficient generation of multi-GW microwave power by klystron-like amplifier, *Rev. Sci. Instrum*., vol. 61, p. 171, 1990.

G. Caryotakis, *et al*., "Gigawatt multibeam klystron (GMBK)," Proc. of 11th Int. Conf. on High-Power Particle Beams, vol. 1, p. 406, 1996.

Gaponov-Grekhov, A. V., and V. L. Granatstein, Eds., Applications of High-Power Microwaves, Artech House Publishers, 1994.

Garate, E. R., D. McWilliams, D. E. Voss, A. L. Lovesee, K. J. Hendricks, T. A. Spencer, M. C. Clark, A. Fisher, "Novel cathode for filed-emission application," *Rev. Sci. inst.*, Vol. 66, pp. 2528-2532, 1995.

Garate, E., R. D. McWilliams, D. E. Voss, A. L. Lovesee, K. J. Hendricks, T. A. Spencer, M. C. Clark and A. Fisher, "Novel cathode for field-emission applications", *Rev. Sci. Instrum.*, vol. 66, no. 3, pp. 2528–2532, March 1995.

Gartner, G., P. Geittner, "Emission Properties of Top-Layer Scandate Cathodes Prepared by LAD," *Appl. Surf. Sci.,* Vol. 111, pp. 11-17, 1997.

Gilmour, A.S., Jr., "Microwave tubes," *Artech House,* 1986.

Ginzburg, N. S., V. I. Krementsov, M. I. Petelin, , P.S. Strelkov, and A.G. Shkvarunets, "Experimental investigation of a high-current relativistic cyclotron maser," *Soviet Phy. Tech. Phy*., vol. 24, pp. 218-222, Feb. 1979.

Glover, F. and M. Laguna : "Tabu Search", Boston, Kluwer Academic Publishers, 1997.

Gold, S. H., A. W.Fliflet, W.M. Manheimer, R.B McCowan, and W.M. Black, "High Peak Power Ka-Band Gyrotron Oscillator Experiment," *Phys. Fluids* vol. 30, p. 2226, 1987.

Gold, S. H., A. W.Fliflet, W.M. Manheimer,M., R.B McCowan , R.C. Lee, V.L.Granatstein, D. L. Hardesty, A.K. Kinkead, and M. Sucy, "High Peak Power Ka-Band Gyrotron Oscillator with Slotted and Unslotted Cavities," *IEEE Trans. Plasma Sci*. vol. 16, no. 2, pp. 142-148, April 1988.

Gold, S. H., A. W. Fliflet, W. M. Manheimer, R. B. McCowan, R. C. Lee, V. L. Granatstein, D. L. Hardesty, A. K. Kinkead, and M. Sucy, "High-peak power Ka-band gyrotron oscillator experiments with slotted and unslotted cavities," *IEEE Trans. Plasma Sci.,* Vol. 16, pp. 142-148, 1988.

Gold, S. H., Gregory S. Nusinovich, "Review of high-power microwave source research," *Rev. Sci. inst.,* vol. 68, pp. 3945-3974, 1997.

Gold, S. H., D. A. Kirkpatrick, A. W. Fliflet, R. B. McCowan, A. K. Kinkead, D. L. Hardesty, M. Sucy, "High voltage milimeter wave gyro travelling wave amplifier," *IEEE Trans. Plasma Sci.* Vol. 18, pp. 1021, 1990.

Granatstein, V.L. and I. Alexeff, "High –Power Microwave Sources," Artech House, Boston-London, 1987.

Granatstein, V. L., M. Herndon, and P. Sprangle, "Gigawatt Microwave Emission From an Intense Relativistic Electron Beam," *Plasma Phys*. vol. 17, no. 1, pp. 23-28, 1975.

Guo Y., Z. Fan , H. He. and D.Chen , "Simulation study of P-band MILO, Institute of applied electronics, Chinese academy of eng. Physics, Mianyang, Sichuan."

Haworth, M. D., J.W. Luginsland, and R.W. Lemke, "Improved cathode design for long pulse MILO operation," *IEEE Trans. Plasma Sci.,* vol.29, pp. 388-392, 2001.

Haworth, M. D., G. Baca, J. Benford, T. Englert, K. Hackett, K. J. Hendricks, D. Henley, M. LaCour, R.W. Lemke, D. Price, and D. Ralph, "Significant pulse-lengthening in a multigigawatt magnetically insulated transmission line oscillator," *IEEE Trans. Plasma Sci.,* Vol. 26, pp. 312-319, 1998.

Haworth, M. D., J. W. Luginsland, and R. W. Lemke, "Evidence of a new pulse-shortening mechanism in a load-limited MILO," *IEEE Trans. Plasma Sci*., Vol. 28, pp. 511-516, 2000.

Haworth, M. D., J. W. Luginsland, and R. W. Lemke, "Improved cathode design for long-pulse MILO operation," *IEEE Trans. Plasma Sci*. Vol. 29, pp. 388-392, 2001.

Haworth, M. D., T. J. Englert, K. J. Hendricks, R. W. Lemke, and J. W. Luginsland, D. S. Shiffler, and T. A. Spencer, "Comprehensive diagnostic suite for a magnetically insulated transmission line oscillator," *Rev. Sci. Inst.,* Vol. 71, pp. 1539-1547, 2000.

Haworth,M.D.,,K.Allen,G.Baca,J.Benford,T.Englert,K.Hackett,K.Hendricks,D.Henley, R.WLemke,D.Price,D.Ralph,M.Sena,D.Shiffler and T.A.Spencer, "Recent progress in the hard tube MILO experiment,"Proc.SPIE,vol.3158,pp.28-39,1997.

Haworth,M.D.,G.Baca,J.Benford,T.Englert,K.Hackett,K.Hendricks,D.Henley,M.Locour ,R.W.Lemke,D.Price,D.Ralph,M.Sena,D.Shiffler and T.A.Spencer, "Significant pulse lengthening in a multi-gigawatt Magnetically Insulated Line Oscillator," *IEEE Trans. Plasma Sci.,*vol.26, p312, 1998.

He, H., "Analysis of the high frequency characteristics of open cavity of MILO of C-band," High power laser part. beams, vol. 18, no. 1, pp. 101– 104, 2006.

He, Y., G. Liu, and Y. Qiu, "A Novel Adaptive Search Strategy of Intensification and Diversification in Tabu Search", *Journal of Computer Research & Development*, vol. 41, pp.162 -166, 2004.

Hoad, R. N. Carter, D. Herke and S. Watkins, "Trends in em susceptibility of it equipment", *IEEE Trans. Electromag. Compability*, vol. 46, pp. 390–395, 2004.
Humphries, S., Jr. "*Charged Particle Beams,* John Wiley & sons, 1990."

Jackson, J. D., Classical electrodynamics, Third edition, John Wiley and sons, 1999.

Jiang, T.,J. Zhang, J. He, J. Ju, Z. Li, and J. Ling, "An Improved Ku-Band Magnetically Insulated Transmission Line Oscillator," *IEEE transaction on plasma science*, vol..43,No.10,pp.3541-3545,Oct. 2015.

Jiang, W., K. Woolverton, J. Dickens and M. Kristiansen, "High power microwave generation by a coaxial virtual cathode oscillator", *IEEE Trans. Plasma Sci.*, vol. 27, no. 5, pp. 1538–1542, Oct. 1999.

Jin ,X and J.Yuan, "Analytical design and simulation rescaling of magnetically insulated transmission lines," *PIERS ONLINE*, vol. 3, no. 6, 2007.

Ju, J.C., Yu-Wei Fan, Hui-Huang Zhong, and T. Shu," A novel dual-frequency magnetically insulated line oscillator," *IEEE Trans. Plasma Sci.,* Vol. 37, pp. 2041-2047, 2009.

Karbhusev, N. I., "A theoretical study of the diocotron instability and drift beam instability of a relativistic electron beam," *Radiophysics and Quantum Electronics,* Vol. 30, pp. 676-681, 1987.

Kennedy, J. and R.C. Eberhart, "Particle swarm optimization", *Proc. IEEE international conference on neural networks,* vol. IV, pp. 1942-1948. IEEE service center, Piscataway, NJ, 1995.

Kervalishvili, G. N., J. I. Javakhishvili, and N. A. Kervalishvili, "Diocotron instability in an annular sheath of gas discharge nonneutral electron plasma," *Phys. Lett.* Vol. 296, pp. 289-294, 2002.

Kesari V. Jain, P.K. and Basu, B. N. "Modeling of axially periodic circular waveguide with combined dielectric and metal loading," *J. Appl. Phys.* Vol. 38, pp.3523-3529, 2005.

Kesari, V, Jain P.K., and Basu,B.N., "Analytical approaches to a disc-loaded cylindrical waveguide for potential application in wide-band Gyro-TWT", *IEEE Trans. Plasma Sci.* vol.32, pp. 2144-2151, 2004.

Kesari, V. "Beam-absent analysis of disc-loaded-coaxial waveguide for application in gyro-TWT (part-1)," *Progress in Electromagnetic Research,* Vol. 109, pp. 211-227, 2010.

Kesari, V., P. K. Jain, and B. N. Basu, "Analysis of circular waveguide loaded with thick annular metal discs for wide-band gyro-TWTs," *IEEE Trans. Plasma Sci.*, vol.33, no. 4, pp. 1358-1365, 2005.

Kim, D. H., H. C. Jung, S. H. Min, M. C. Wang, M. J. Rhee and G. S. Park, "Experimental investigation of giga-watt magnetically insulated transmission line oscillator (MILO) by improved axial power extraction," *IEEE International Vacuum Electron Sources,* pp. 561-562, 2006.

Kim, D. H., H. C. Jung, S. H. Min, S. H. Shin, and G. S. Park, "Dynamics of mode competition in a gigawatt-class magnetically insulated line oscillator," *Appl. Phys. Lett.,* Vol. 90, pp. 124103, 2007.

Kim, D. H., H. C. Jung, S. H. Min, S. H. Shin, M. J. Rhee, G. S. Park, C. H. Kim, and D. W. Yim., "Experimental investigation of giga-watts magnetically insulated transmission line oscillator (MILO)," *Proc. IEEE Int. Vacuum Electron. Conf.*, pp.561-562, 2006.

Kim, D. H., H. C. Jung, S. H. Shin, and M. J. Rhee, "Simulation study on magnetically insulated line oscillator for efficient operation," School of physics and astronomy, Seoul national university, Shilimdong , Korea, pp. 228-229.

Kleen, W. J., Electronics of Microwave Tubes, Academic press 1958.

Knowles, T. R., "Carbon velvet cathodes," *NRL, Cathodes Workshop,* 2001.

Kory, C. L., "Investigation of Fully Three-Dimensional Helical RF Field Effects on TWT Beam/Circuit Interaction," *IEEE Trans. Elect. Devices*, vol. 48, pp.1718-1826, 2001.

Kory, C. L., and James A. Dayton .Jr, "Design of 650 GHz Helical BWO using CST Studio Suite," *Proc. IVEC,* pp 392-393, 2009.

Krasik, Y. E., D. A. Krokmal, and J. Felsteiner, "Emission properties of different cathodes at $E \leq 10^5$ V/cm," *J. Appl. Phys.,* Vol. 89, pp. 2379-2399, 2001.

Krishnamacharim, R. T., "Dawn of the E-Bomb**:** High-Power Microwave technology and Military implications for India," *South Asia Analysis Group*, pp. 1089, 2004.

Langmuir, I., and K. B. Blodgett, "Currents limited by space charge between coaxial cylinders," *Physical Review,* Vol. 22, pp. 347-355, 1923.

Lau, Y. Y., Theory of crossed field devices and a comparative study of other radiation sources, High power microwave sources, Artech House, 1987.

Lau, Y. Y., V.L. Granatstein, and I. Alexeff, "Theory of crossed-field devices and a comparative study of other radiation sources," Eds. Boston, MA: Artech House, pp. 309-349, 1987.

Lau,Y.Y, M. Friedman, J. Krall, and V. Serlin, "Relativistic klystron amplifier driven by modulated intense relativistic electron beams, *IEEE Trans. Plasma Sci*., vol. 18, no. 3, pp. 553-569, June, 1990.

Lawconnell, R. I., and J. Neri, "Theory of magnetically insulated electron flows in coaxial pulsed power transmission lines," *Phys. Fluids B.,* Vol. 2, pp. 629-639, 1990.

Lemke, R. W., "Linear stability of relativistic space-charge flow in a magnetically insulated transmission line oscillator*," J. Appl. Phys,* Vol. 66, pp. 1089-1094, 1989.

Lemke, R. W., and M. C. Clark, "Theory and simulation of high power microwave generation in a magnetically insulated transmission line oscillator," *J. Appl. Phys.,* Vol. 62, pp. 3436-3440, 1987.

Lemke, R. W., G. E. Demuth, and A. W. Biggs, "Theoretical and experimental investigation of axial power extraction from a magnetically insulated transmission line oscillator," *Intense Microwave and Particle Beams, Proc. SPIE 1226, H. E. Brandt Ed.,* pp. 199-206, 1990.

Lemke, R. W., M.C. Clark, and S.E. Calico, "Four cavity efficiency enhanced magnetically Insulated Line Oscillator," *US Patent 5742209,* 1998.

Lemke, R. W., S. E. Calico, and M. C. Clark, "Investigation of a load-limited, magnetically insulated transmission line oscillator (MILO)," *IEEE Trans. Plasma Sci..,* Vol. 25, pp. 364-374, 1997.

Lemke, R.W., M. C. Clark, and S. E. Calico, US Patent No. 5742209, 1998.

Levush, B, T. M. Antonsen, Jr., A. Bromborsky, W. R. Lou, and Y. Carmel, "Theory of relativistic backward wave oscillators with end reflections," *IEEE Trans. Plasma Sci.*, vol. 20, no. 3, pp. 263-280, June, 1992.

LI, Z.Q., H.H. Zhong, Y.W. Fan . and T.Shu, B.L QIAN , L.R. XU, Z. Y.Song, "Investigation of a S-Band Tapered magnetically insulated transmission line oscillator," *Chinese Physics Lett.,* vol. 26, No.5,055201,2009.

Lie, L., L. Limin, X. Zhang, J. Wen, H. Wan, and H. Zhong , "Carbon fibre based cathodes for magnetically insulated transmission line oscillator operation," *Applied Phys. Lett.* Vol.91, pp. 161504(1-3), 2007.

Ling, G. S. and C. W. Yuan, "Design of a Vlasov antenna with reflector", *International Journal of Electronics*, vol. 91, No. 4, pp.253-258, Apr. 2004.

Litz, M. S., J. Golden, "Low voltage, explosive whisker emission cathodes studies," *Proceedings of the Euroem 94 International Symposium, Bordeaux (France),* pp. 209-215, 1994.

Liu Lie, Li, Limin, Zhang Xiaoping, Wen Jianchun, Wan Hong, and Zhong Huihuang, "Carbon fiber based cathodes for magnetically insulated transmission line oscillator operation," *Applied Phys. Lett*., 2007.

Lovelace, R. V., and E. Ott "Theory of magnetic insulation," Phys. Fluids, Vol. 17, p. 1263-1268, 1974.

Marder, B. M., "Simulated behavior of the magnetically insulated oscillator," *Journal of Appl. Phys.*, Vol. 65, pp. 1338-1349, 1989.

Marshall, T. C., *Free-Electron Lasers,* Chap. 7, Macmillan, New York, 1985.

Marshall, T.C., "Free-Electron Lasers," Chap. 7, Macmillan, New York, 1985.

Mendel, C. W., D. B. Seidel, S. E. Rosenthal, "A simple theory of magnetic insulation from basic physical consideration," *Laser and Particle Beams,* Vol. 1, pp. 311-320 1983.

Mendel, C.W , D. B. Seidel, and S. A. Slutz, "A general theory of Magnetically insulated electron flow", *Int. Journal Phys. Fluids*, vol. 26, no. 12, pp.3628-3635,1983.

Mendel Jr, C .W., "Planar one-dimensional magnetically insulated electron flow for arbitrary canonical-momentum distribution," J. Applied Physics,Vol.50,p.3830,1970.

Mendel Jr, C. W., and S. E. Rosenthal, "Modeling magnetically insulated devices using flow impedance," *Phys. Plasmas,* Vol. 2, pp. 1332-1334, 1995.

Menninger, W. L., B.G. Danly, and R.J. Temkin, "Multi-megawatt Relativistic Harmonic Gyrotron Traveling- Wave Tube Amplifier Experiments," *IEEE Trans. Plasma Sci*. vol. 24, no. 3, pp. 687-699, June 1996.

Michael D. Haworth, Keith L. Cartwright, John W. Luginsland, Donald A. Shiffler, and Ryan J. Umstattd, "Improved electrostatic design for MILO cathodes," *IEEE Trans. Plasma Sci*., Vol. 30, no. 3, 2002.

Microwave Studio Suite: "Computer System Technology (CST)," AG, www.cst.com.

Miller R.B., "Mechanism of explosive electron emission for dielectric fiber (velvet) cathodes," *Journal of Applied Physics,* vol. 84, pp. 3880-3889, 1998.

Miller, R. B., "An Introduction to the Physics of Intense Charged Particle Beams," New York, NY: Plenum, 1982.

Miller, R. B., "Mechanism of explosive electron emission for dielectric fiber (velvet) cathodes," *j. Appl. Phys*., Vol. 84, pp. 3880-3889, 1998.

Miller,R, W. McCullough, K. Lancaster and C. Muehlenweg, "Superreltron theory and experiments", *IEEE Trans. Plasma Sci.*, vol. 20, pp. 332–343, 1992.

Minami, K., Y.Carmel, and V. L. Granatstein, "Linear theory of electromagnetic wave generation in a plasma loaded corrugation wall resonator," *IEEE Trans. Plasma Sci.,* vol.18, no. 3, pp. 537-545, 1990.

Nallasamy, V., S .K. Datta, SUM Reddy and P. K. Jain, "Efficiency Enhancement of an S-band Magnetically Insulated Line Oscillator," *International Journal of Microwave and Optical Technology* (*IJMOT*), vol.11, No.5, pp. 324-331, Sept 2016.

Nallasamy, V., "Sources for high Power Microwaves", *Defence Science Spectrum*, pp. 225-234, February 2012.

Palevski, A., and G. Bekefi, "Microwave emission from pulsed relativistic E-beam diodes, II: The multi-resonator magnetron," *Phys. Fluids*, vol. 22, 985, 1979.

Parker, R. K., "Explosive electron emission and the characteristics of high current electron flow," *Air Force Weapons Laboratory, AFWLTR-73-92, Kirtland Air – Force base,* New Mexico, 1974.

Parker, R. K., R. H. Jackson, S. H. Gold, H. P. Freund, V. L. Granatstein, P. C. Efthimion, M. Herndon, and A. K. Kinkead. "Axial magnetic-field effects in a collective-interaction free-electron laser at millimeter wavelengths," *Physical Rev. Lett.,* Vol. 48, pp. 238, 1982.

Phillips, R. M., *IRE Trans. Electron Devices,* ED-7, 231, 1960.

Pierce, J. R., Theory and Design of Electron Beams, D. Van Nostrand Company 1949.

Price, D., and J. Benford, "General Scaling of Pulse Shortening in Explosive-Emission-Driven Microwave Sources," *IEEE Trans. Plasma Sci.,* Vol. 26, pp. 256-262, 1998.

Qian, Bao-Liang, Yong-Gui Liu, Chuan-Lu Li, and Che-Bo Liu, "Two-dimensional analysis of the relativistic parapotential electron flow in a magnetically insulated transmission line oscillator (MILO)," *IEEE Trans. Plasma Sci*., Vol. 28, pp. 760-766, 2000.

Qiang, WU. J. , "Dispersion Characteristics of a new slow-wave structure," *Chin.Phys. Lett.* vol.21, pp.2231-2233, 2004.

Qin, F., D. Wang, Dai-Bing, and Zhi-Kai Fan, "Simulation investigation of L-band ladder cathode MILO," *IEEE Trans. Plasma Sci*., Vol. 37, pp. 1921-1924, 2009.

Qin, F., Dong Wang, Dai-Bing Chen, and Jie Wen, "Simulation Investigation of S-Band Higher-Order-Mode Depressed MILO," IEEE Trans. Plasma Sci., vol. 40, no. 7, pp. 1933–1936, July 2012.

Qin, F., Dong Wang, Jie Wen, Dai-Bing Chen, and Zhi-Kai Fan, "A novel method to depress higher order mode generation in MILO," IEEE Trans. Plasma Sci., vol. 39, no. 1, pp. 545-549, Jan. 2011.

Quang, Li. Zhi, Zhong, Hui-Huang, Fan Yu Wei, and Shu Ting, "Investigation of a Tapered magnetically insulated transmission line oscillator," *Chin. Phys. Society,* Vol. 26, 2009.

Ragha, L.K., and M.S Bhatia , "Numerical Methods for Bio-electromagnetic Computation: A General Perspective", *Proceedings of SPIT-IEEE Colloquium and International Conference*, vol. 2, pp. 94-99, 2007.

Ron, A, A. Mondelli and N. Rostoker, "Equilibria for magnetic insulation," *IEEE Transaction on Plasma Science*, pp. 85- 93,1973.

Roy, A., R. Menon, S. Mitra, S. Kumar, V. Sharma, K. Nagesh, K. Mittal and D. Chakravarthy, "Plasma expansion and fast gap closure in a highpower electron-beam diode", *Phys. Plasmas*, vol.16, p. 053103, May 2009.

Ruth, B. G., R. K. Dahlstrom, C. D. Schlesiger, and L. F. Libelo, " Design and low-power testing of a microwave Vlasov mode converter ", *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, pp.1277-1280, 1989.

Scalar network analyser (SNS) , user's manual

Schamiloglu, E., "High power microwave sources and app cations,*" IEEE MTT-S International,* Vol. 2, pp. 1001-1004, 2004.

Serene,B, R.Varma, Jayanta, "A comparative study of GA, PSO and APSO: Feed point optimization of a patch antenna", *International Journal of Scientific and Research Publications*, Volume 3, Issue 5, May 2013 .

Sexton, R.S., B. Alidaee, R.E. Dorsey, "Global Optimization for Artificial Neural Networks", *European Journal Operational Research*, vol. 106, pp.570-584, 1998 .

Shiffler, D., G. Baca, T. Englert, M. D. Haworth, K. J. Hendricks, D. Henley, M. Sena, and T. A. Spencer, "Investigation of RF breakdowns on the MILO," *IEEE Trans. Plasma Sci*., Vol. 26, pp. 304-311, 1998.

Shiffler, D., M. Ruebush, M. Haworth, R. Umstattd, M. LaCour, K. Golby, D. Zagar and T. Knowles, "Carbon velvet field-emission cathode", *Rev. Sci. Instrum.*, vol. 73, no. 12, pp. 4358–4362, Dec. 2002.

Shiffler, D., M. Ruebush, M. LaCour, K. Golby, R. Umstattd, M. C. Clark, J. Luginsland, D. Zagar and M. Sena, "Emission uniformity and emission area of explosive field emission cathodes", *Appl. Phys. Lett.*, vol. 79, no. 18, pp. 2871–2873, Oct. 2001.

Shiffler, D., M. Ruebush, M. Haworth, R. Umstattd, M. LaCour, K. Golby, D. Zagar, and T. Knowles, "Carbon velvet field-emission cathode," *Rev. Sci. Inst.,* Vol. 73, pp. 4358-4362, 2002.

Smith, I.D , P.D. Champney and J. M. Creedon, " Magnetic Insulation," *IEEE int. Pulsed conference*, pp.8-11,1976.

Spencer, T. A., K. J. Hendricks, J. W. Luginslandand, M. D. Stump, "Dynamics of space charge limiting current in gyro type devices, "*IEEE Trans. Plasma Sci.,* Vol. 24, pp. 630, 1996.

Sullivan, D. J. “High power microwave generation using virtual cathode oscillator,” *IEEE Trans. Nucl. Sci.* NS-30, p. 3426, 1983.

Umstattd, R., D. Shiffler, J. Luginsland, M. D. Haworth, “Diode studies for HPM Applications at AFRL,”*NRL Cathode Workshop*, 2001.

Voronkov, S. N., V. I. Krementsov, P.S. Strelkov, and A.G. Shkvarunets, “Stimulated cyclotron radiation at millimeter wavelengths from a high-power relativistic electron beam,” *Soviet Phy. Tech. Phy*., vol. 52, pp. 106-108, Jan. 1982.

Walter, M. T., R. M. Gilgenbach, J. W. Luginsland, J. M. Hochman, J. I. Rintamaki, R. L. Jaynes, Y. Y. Lau, and T. A. Spencer, “Effect of tapering on Gyrotron backward wave oscillator,” *IEEE Trans. Plasma Sci.* Vol. 24, pp. 636-647, 1996.

Wang, D., “Design and Simulation of Double Ladder Cathode Magnetically Insulated Transmission Oscillator,” High power laser part. beams, vol. 19, no. 4, pp. 647–650, 2007.

Wang, D., “Simulation of S-band Magnetically Insulated Transmission Oscillator,” High power laser part. beams, vol. 19, no. 11, pp. 1861–1864, 2007.

Wang, D., Z. K. Fan, D. B. Chen, and J. Deng, “Investigation of dispersion characteristics in coaxial disc-loaded slow-wave structures with both symmetric and asymmetric modes,” *IEEE Trans. Plasma Sci.*, vol. 35, pp. 1070–1074, 2007.

Wang, D.,J. Fan, D. Chen , and J. Deng , “Rigorous analysis of the coaxial disk-loaded waveguide slow-wave structures,” *Proc. Int. Conf. Microwave and Millimeter wave Tech*., Apr. 18-21, 2007.

Wang, D.,Z.K. Fan,D.B. Chen, and J. Deng, “Investigation of dispersion characteristics in coaxial disc-loaded slow wave structures with both symmetric and asymmetric modes”, *IEEE Trans. Plasma Sci.,* vol. 35, pp.1070-1074, 2007.

Wang,D. ,Dai-Bing Chen and Z. K. Fan , “Improved Bifrequency magnetically insulated transmission line oscillator,”IEEE Trans. Plasma Sci.,Vol. 38, No.1,pp.19-25, Jan.2010.

Wen,J., Dai-bing Chen, Dong Wang, and Fen Qin, “Preliminary Experimental Research on

Xiao, R., W. Song, Z. Song, J. Sun, H. Shao, and C. Chen, “ High efficiency X-band magnetically insulated line oscillator with separate cathode,” *Phys. Plasmas*, Vol. 17, pp. 043109, 2010.

Xiao, R., Y. Zhang, H. Shao, and J. Sun, "An inward-emitting magnetically insulated line oscillator," *IEEE Trans. Plasma Sci*., Vol. 37, pp. 1925-1929, 2009.

Xiao,R., Jun Sun, ChanghuaChen, Y Zhang and Hao Shao, "High efficiency annular Magnetically insulated line oscillator-Transit Time Oscillator with three separate frequencies in three bands," Journal of Applied Physics,106,033308,2009.

Yang Y., and W. Ding, "A novel method for increasing magnetically insulated transmission line oscillator frequency," *Phys. plasma,* Vol. 8, pp. 3443-3444, 2001.

Yang, W., "Numerical study of a simply constructed magnetically insulated transmission line oscillator," *IEEE Trans. Plasma Sci.,* vol. 36, pp. 2801-2804, 2008.

Yanhua, G, F. Zhikai, and H. Hu, "Simulation investigation of C-band magnetically insulated line oscillator," *IEEE 2007, Interaction symposium on microwave,* pp. 1339-1344, 2007.

Yee, K. S., "Numerical solution of initial boundary value problems involving Maxwell's equation in isotropic media," *IEEE Trans on Antenna and Propagation,* vol. 14, pp. 302-307, 1966.

Yu Wei, F., Z. Hui-Huang, S. Ting, L. Zhi Quang, "Investigation of an X-band magnetically insulated transmission line oscillator," *Chin. Phys. Society, and IOP publication Ltd,* Vol. 17, pp. 1804, 2008.

Yu, J.F., H.H. Wei,Zhong and T.Shu, "Conventional X-band magnetically insulated transmission line oscillator,"Physics of Plasmas,16,073103,2009.

Yu-Wei, F., S. Ting, L. Yong-Gui, Z. Hui-Huang, L. Zhi-Qiang, W. Yong, Z. Yan-Song, and L. Ling, "A compact magnetically insulated line oscillator with new-type beam dump," *Chin. Phys. Lett.,* Vol. 22, pp. 164, 2005.

Yu-Wei, F., Z. Hui-Huang, S. Ting, and Li Zhi-Qiang, "Complex magnetically insulated transmission line oscillator," *Phys. plasma,* Vol. 15, pp. 083108, 2008.

Zhang, Y., and X. Zhou, "Rigorous analysis of the disc-loaded waveguide slow wave structures *Int. J. Infrared Millimeter Waves,* vol. 24, pp. 525-535, 2003.

Zhang, Y.,X. Zhou, and J. Li, "Study of disk-loaded waveguide filled with plasma", *Int. J. Infrared Millimeter Waves,* vol. 24, pp. 2085-1094, 2003.

AUTHOR’S RELEVANT PUBLICATIONS

Publications in Referred Journals:

1. **V Nallasamy,** S K Datta, SUM Reddy and P K Jain, “Efficiency Enhancement of an S-band Magnetically Insulated Line Oscillator,” *International Journal of Microwave and Optical Technology (IJMOT)*, vol.11, No.5, pp. 324-331, Sept 2016
2. **V Nallasamy,** “Sources for high Power Microwaves”, *Defence Science Spectrum*, pp. 225-234, February 2012.
3. **V Nallasamy,** C Narasimhamurthy, B Geetha, Sanjay Kumar Gupta, Subrata Kumar Datta, SUM Reddy and P K Jain, “Electromagnetic Simulation and Experimental Characterization of RF Interaction Structure of an S-band Magnetically Insulated Line Oscillator,” *Journal of Electromagnetic Waves and Applications(JEMWA)*, - accepted for publication .
4. **V Nallasamy,** S K Datta, SUM Reddy and P K Jain, “Advances and Present Trends in Magnetically Insulated Line Oscillator” – To be Communicated to IJMOT

Publications in International/National Conferences/ Symposium Proceedings:

1. **V Nallasamy**, S K Datta, SUM Reddy and P K Jain, “Design and Simulation of Magnetically Insulated Line Oscillator,” Proceedings of National conference on Vacuum Electronic Devices and Applications, Sep .21-24,2012.
2. U Shanmuganathan, Saket Khandekar, **V Nallasamy** and SUM Reddy**,** “ Design and Development of a Magnetically Insulated Transmission line for 200J Pulsed power system,” Proceedings of National conference on Emerging trends in Vacuum Electronic Devices and Applications,Dec.3-5,2015

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,

VOL.11, NO.5, SEPT 2016

Efficiency Enhancement of an S-band Magnetically Insulated Line Oscillator

V Nallasamy*[1], S K Datta[2], SUM Reddy[3] and P K Jain[4]

*[1] Microwave Tube Research and Development Centre, Bangalore-560013, INDIA.
[2]Centre of Research in Microwave Tubes, Department of Electronics Engineering,
Indian Institute Technology (Banaras Hindu University), Varanasi-221005, INDIA.
Email: [1]nallasamy@mtrdc.drdo.in, [2]skd@ mtrdc.drdo.in, [3]reddy@mtrdc.drdo.in, [4] pkjain.ece@iitbhu.ac.in

***Abstract*- An improved Magnetically Insulated Line Oscillator (MILO) operating in S-band was designed using analytical formulation and was simulated using 3D-electromagnetic particle-in-cell (PIC) code. The Dispersion characteristics of the RF interaction structure was analytically obtained using equivalent circuit approach, and subsequently the performance was optimized using particle-in-cell analysis for operation around π-mode resonant frequency of 3.3 GHz. The region of operation of this MILO was obtained under para-potential flow using Hull-cut off and Buneman-Hartree conditions. The design was optimized for improving the efficiency by suitable tailoring of the lengths of cathode, beam dump, extractor cavity gap and the position of stub at the output of the device. The design was performed for 500 kV, 47.5 kA and simulated output power of around 6 GW in TM_{01} mode could be achieved at the frequency of 3.1 GHz with the power conversion efficiency of around 25%.**

***Index Terms*- Electromagnetic PIC simulation, Dispersion relation, high power microwave, Magnetically Insulated Line Oscillator (MILO).**

I. INTRODUCTION

MILO is a GW-class cylindrical crossed-field oscillator invented by Lemke and Clark [1] in 1987, and became popular for its potential as a high-power microwave (HPM) source for military applications (Fig.1). It has a unique magnetic self-insulating property that enables the tube to handle extremely large input power (tens to hundreds of GW) at a modest applied voltage (several hundred kilovolts). It does not require any externally applied DC magnetic field, which allows the conceptualization of a compact and light weight HPM source. At high voltages, electrons are emitted from the cathode but the current carried by the body (anode) creates a sufficiently strong magnetic field such that these electrons cannot cross the interaction gap. The electrons drift axially in the crossed electric and self-generated magnetic fields. The slow-wave structure (SWS) facilitates the interaction between the axially drifting electrons (the region adjacent to the cathode) and the axially directed slow electromagnetic wave to generate microwaves. However, it suffers from the fundamental limitation of low RF conversion efficiency. This is due to the utilization of maximum load current for generating the self-magnetic field [2–4]. The first ever MILO developed by Lemke *et al*., [4] that has output power of 2.1GW power at L-band with an efficiency of 10.3%. The highest efficiency in an experimental MILO has been achieved so far is ~11%.

Marder simulated the behavior of MILO with 47 kA, 195 kV electron beam to get ~2GW at L-band with an efficiency of ~11% [3]. Kim *et al*., experimentally studied an axial mode competition in a GW MILO with a pulse duration of 130 ns and verified through a PIC code [6]. Cousin *et al*., developed a compact MILO based on the U.S. Air Force geometry that was operated in 3π/4 mode with a beam voltage of 600 kV [7]. In 2009, Li *et al*., tested an improved tapered MILO for 2GW of peak RF power in TM_{01} mode at 2.63 GHz with a conversion efficiency of ~11% [8]. In 1998, Eastwood *et al*., developed a tapered MILO with a simulation efficiency of ~30% [9]. Qin *et al*., simulated an S-band higher order mode depressed MILO based on an existing L-band

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.11, NO.5, SEPT 2016

ladder cathode MILO at 1.2GHz using an electron beam of 830 kV interacting with a transverse electromagnetic (TEM) mode to obtain an RF power of ~6GW at 2.48 GHz [10].

In this article, the design and simulation of an S-band MILO is presented to improve its overall efficiency by reducing the total length and proper impedance matching at the output by using stubs. The rest of the article is organized as follows: the analytical design methodology and the dispersion of MILO are presented in Section II. The 3D modeling and PIC simulation of the improved MILO are narrated in Section III. The technique of efficiency enhancement is briefed in Section IV and the conclusion is drawn in Section V.

II. DESIGN METHODLOGY

We have considered a MILO with the slow-wave structure comprising periodically spaced cavities formed by placing apertures in a smooth waveguide, as shown in Fig. 2. The slow-wave structure supports number of slow-wave modes. Suitable phase synchronism between any one of these electromagnetic modes and the drifting electrons (with velocity $v_d = E_o / B_o$, where E_o and B_o are the electric field in radial direction and magnetic field in azimuthal direction, respectively) results in efficient conversion of beam energy to RF energy.

The resonant frequency, ω_o of an individual SWS cavity of the MILO can be expressed in terms of the circuit parameters following equivalent circuit approach as [11]:

$$\omega_0 = \left(\frac{\mu_0 z d}{4\pi r_0} \left[2\varepsilon_0 r_i \ln\left(\frac{z/2 + w}{z/2} \right) + \frac{2\pi\varepsilon_0}{3zd}\left(r_0^3 + 2r_i^3 - 3r_0 r_i^2 \right) \right] \right)^{-1/2} \quad (1)$$

where, μ_0 is the permeability of free-space; z is the distance between the SWS apertures; r_0 and r_i are the outer and inner radii of the SWS vane; $d = r_o - r_i$ is the vane height; w is the thickness of the SWS vane; r_c is the cathode radius; s is the circuit periodicity; and $l = r_i - r_c$ is the free space gap between anode to cathode . For a slow-wave structure comprised of N number of cavities, the resonance condition would necessitate the following condition to satisfy:

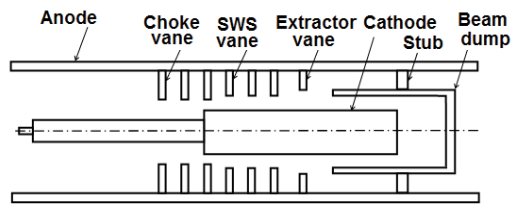

Fig.1. Schematic of Magnetically Insulated Line Oscillator.

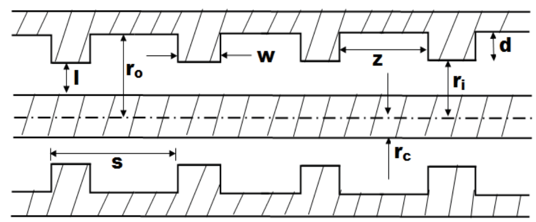

Fig.2. Schematic of coaxial disk loaded SWS.

$$2N\varphi = 2k\pi \quad (2)$$

where, N is the number of SWS cavities; k is an integer and φ is the phase difference between the adjacent cavities. The resonant frequency of the coupled cavity stack, ω_{ok} can be now given as [11]:

$$\omega_{0k} = \omega_0 \left(1 + \frac{ \frac{2\pi\varepsilon_0 w}{\ln(r_i / r_c)} + 8\varepsilon_0 \left[z + \left(r_i - \frac{2l}{\pi} \right) \ln\left(1 + \frac{\pi z}{2l} \right) \right] }{ 2\left[2\varepsilon_0 r_i \ln\left(1 + \frac{2w}{z} \right) + \frac{2\pi\varepsilon_0}{3zd}\left(r_0^3 + 2r_i^3 - 3r_0 r_i^2 \right) \right] } \left(\frac{1}{1-\cos\phi} \right) \right)^{-1/2} \quad (3)$$

When cathode current becomes higher than the critical current, the self-magnetic field generated confines the electrons and it does not reach up to the anode. The electrons derive equipotential surfaces and move perpendicular to the crossed

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.11, NO.5, SEPT 2016

electric and magnetic fields. The minimum current or critical current I_{cr} required to insulate the beam is defined as [12]

$$I_{cr} = I_0 \sqrt{\gamma_o^2 - 1} / \ln(r_i / r_c) = \frac{4\pi m_0 c^3 \varepsilon_o \sqrt{\gamma_o^2 - 1}}{e \ln(r_i / r_c)} \quad (4)$$

where, r_c and r_i are the cathode and anode radii, respectively; I_o is the starting current for oscillation, e is the electron charge and m_o is the electron mass at rest; $\gamma_o=(1-\beta^2)^{-1/2}$ is the relativistic mass factor with $\beta=v_d/c$ as the normalized electronic drift velocity with respect to the velocity of electromagnetic wave in free-space as evaluated at the anode. As the insulated electron flow fills the anode-to-cathode gap (A-K-gap), the total anode current or para-potential current, I_p becomes [12]

$$I_p = \frac{I_0 \gamma_o \ln\left(\gamma_0 + \sqrt{\gamma_o^2 - 1}\right)}{2 \ln(r_i / r_c)} \quad (5)$$

Under the condition of Diocotron instability [13], few of the electrons of the beam reach the anode and few others remain at the magnetic cutoff, while the other electrons migrate towards the anode in bunch form (usually called as spokes). The mode of oscillation of MILO is established when electron drift velocity is slightly greater than the phase velocity of the RF wave. The condition of synchronism is given as [14]:

$$v_d = \frac{E_0}{B_0} = \frac{V_0}{2\ln(r_i / r_c)}\left(\frac{2\pi r}{\mu_0 I_t}\right) = \frac{2\pi\varepsilon_0 c^2}{\ln(r_i / r_c)}\left(\frac{V_0}{I_t}\right) \cong 0.3\,c \quad (6)$$

where, v_d is the electron drift velocity; ε_o is the permittivity of free-space; I_t is the total anode current. The RF phase velocity, v_φ at which electronic interaction could take place can be now expressed under the condition of synchronism, $v_\varphi \approx v_d$ as [14]:

$$v_\varphi = \frac{s}{2d\,c} \cong 0.3c = \frac{\omega}{\beta_0} = \frac{2\pi f}{(\pi / s)} = 2s\,f \quad (7)$$

where, ω is the angular frequency, s is the periodicity of the slow-wave structure (SWS), d is the vane height, f is the operating frequency, and β_o is the axial propagation constant. In order to complete the design, it would be now required to arrive at the length of the load, the length of the cathode and the efficiency of the device. These parameters are arrived at from the consideration of Hull cut-off and Buneman-Hartree conditions. The cathode current I_c under Hull cut-off criteria is defined as [14]

$$I_C = \frac{8500}{\ln(r_i / r_c)}\left[\frac{eV_H}{m_0 c^2}\left(2 + \frac{eV_H}{m_0 c^2}\right)\right]^{\frac{1}{2}} \quad (\textit{Hull cut-off}) \quad (8)$$

Here, V_H is the Hull cut-off voltage; e and m_o are the charge and mass of electrons at rest, respectively. The relation between the cathode current, I_c and the Buneman-Hartree voltage, V_{BH} is given by [14]

$$I_C = \frac{8500}{\beta_0 \ln(r_i / r_c)}\left[\frac{eV_{BH}}{m_0 c^2}\left(1 - \sqrt{1 - \beta^2}\right)\right] \quad (9)$$

For a given operating voltage, when the minimum load length is decided at the condition of charging current reaching the value of critical current, I_{cr}. Under such condition, the minimum length of load, $L_{C\,min}$ is defined by [4],

$$L_{C\min} = 2r_c \ln\left(\frac{r_i}{r_c}\right)\frac{\sqrt{\gamma^2 - 1}}{\left[G(\gamma_0)\right]^2} \quad (10)$$

where, $G(\gamma_0) \approx 2\left(\gamma_0^{1/2} - 0.847\right)$. The length of the cathode, L_{SE} is arrived from the perveance of the device $\mu = I_C / V_o^{3/2}$, given as [15]:

$$L_{SE} = 6.82 \times 10^4 \mu r_i \left(\ln(r_i / r_c)\right)^2 \quad (11)$$

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.11, NO.5, SEPT 2016

where, μ is the diode perveance that depends on geometrical parameters, I_c is the cathode current and V_o is the cathode voltage. The corresponding maximum efficiency, η_{max} of the MILO relative to the input beam power is given by [4]:

$$\eta_{max} = \frac{P_{max}}{V_0 I_p} = 0.32\left(\frac{I_{s,max}}{I_p}\right) = 0.32\left[1-\left(\frac{I_{cr}}{I_p}\right)\right] \quad (12)$$

where, $P_{max} = 0.32*I_{s,max}*V_o$ and $I_{s,max} = I_p - I_{cr}$, is the maximum total dc spoke current, V_o is dc A-K gap voltage, and P_{max} is the corresponding output power of the MILO. The maximum power conversion efficiency is possible to be obtained for the condition of transit angle corresponding to the gap approaching π which is accounted for with the numerical value of 0.32 as given in the equation (12). However, both simulations and experiments for a load-limited MILO have shown efficiencies quite close to those predicted by (12). The region of operation of the proposed device with r_c = 25 mm, r_i = 40 mm, s =13 mm, and $2d$ = 42.8 mm as obtained from the analysis is shown in Fig. 3. The dispersion characteristics of the four cavity slow wave structure operating in π-mode at the frequency of 3.3 GHz is shown in Fig. 4 as computed using the equivalent circuit analysis. The device operates at a constant voltage within the regime $V_{BH} < V < V_H$ with the electron beam intensity limited by self-generated magnetic field. The Buneman-Hartree condition does not become prevalent due to the corresponding plot remains below the para-potential current.

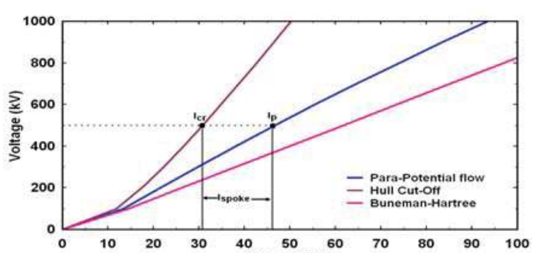

Fig. 3. Region of operation of the MILO for r_c= 25 mm, r_i = 40 mm, s=13 mm, $2d$ = 42.8 mm.

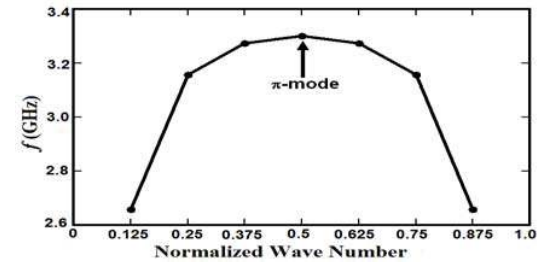

Fig. 4. Dispersion characteristics of the four cavity SWS.

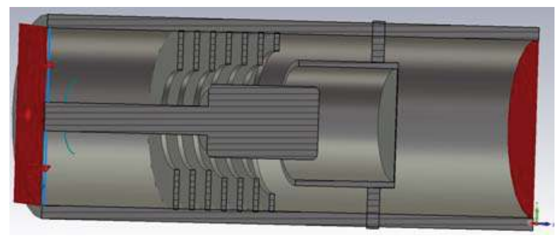

Fig. 5. 3D model of the proposed MILO in CST environment.

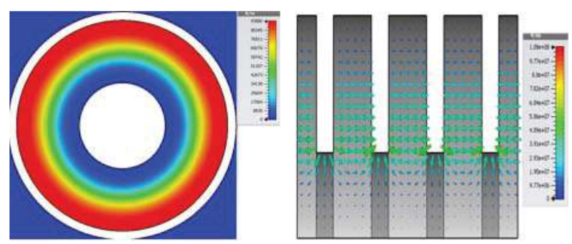

Fig. 6. (a) TM_{01} field pattern, and (b) π-mode in SWS of MILO.

III. MODELING AND SIMULATION OF MILO

A. Beam-Absent Cold Simulation

In our design, the RF section comprises seven vanes: three choke vanes, three SWS vanes, and one extractor vane. The first three vanes (choke vanes) constitute the RF choke cavity that is operated at frequency less than the pi-mode frequency. The dimensions of the next three vanes (SWS vanes) decide the frequency of oscillation as the beam-wave interaction takes place in this region. The inner radius of the last vane (extractor vane) is kept larger than SWS vanes and it plays a vital role in extracting RF energy from the interaction region. The extractor vane and beam dump form the RF extracting

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.11, NO.5, SEPT 2016

cavity. The 3-D modeling of the device was carried out using CST Studio with adaptive mesh refinement. A 3-D schematic of the MILO with short-length cathode is shown in Fig. 5. The design parameters used in the present model are shown in Table 1. All the vanes including choke, SWS, beam dump, cathode, anode, and stubs of MILO structure have been modeled using a perfect electric conductor (PEC) with background as vacuum. The MILO structure has been modeled and simulated in the linear co-ordinate system using hexahedral meshing. Both electric and magnetic fields satisfy the boundary conditions imposed by the walls of the RF circuit. The Eigen-mode analysis has been carried out for the desired TM_{01}-mode in the SWS (Fig. 6). The *E*-field in adjacent cavities are 180° out of phase which confirms the π-mode of operation at 3.3 GHz. The field distribution associated with π-mode produces the strongest coupling to the electron beam with high Q (quality factor) space-harmonics. To maximize the power output in our improved MILO, four short-circuited stubs are placed at 90 degrees apart that provide return path for electron beam. These are mechanically joined to the extractor and anode for impedance matching and also acting as a short circuit for dc but an open circuit for RF.

B. Beam-present Hot Simulation

A few assumptions are used for the PIC simulation: the electric and magnetic fields are assumed to be confined to the space within the RF interaction circuit, dielectric loss is negligible, and the power loss at the metallic boundaries is also negligible. For the beam-present simulation, four discrete ports at 90° apart have been defined at the input port of the MILO for applying high voltage between the cathode and the anode. In the RF circuit of MILO, electrons have been considered as uniformly longitudinally distributed, and their evolution along the axial direction in the presence of RF noise has been monitored in time domain. A beam voltage of 500kV with the rise time of 1ns was applied between cathode and anode at the input port to facilitate generation of electron beam due to explosive emission from the surface of a cylindrical velvet cathode.

Table 1: Optimized Design Dimensions of MILO

Parameters	Designed Parameters	Optimized Parameters
SWS vane radius (r_i)	40 mm	39 mm
Extractor vane radius (r_{ex})	48 mm	49 mm
Cavity Period (s)	12.9 mm	13 mm
Beam dump inner radius	40 mm	39 mm
Beam Dump outer radius	44 mm	43 mm
Beam Dump length	164.4 mm	84.4 mm
Cathode projection inside Beam Dump	123.4 mm	7.4 mm
Length of cathode	200mm	80mm
Total length of MILO	373.8mm	289.8mm

Due to the self-generated magnetic field, electron beam remains insulated between the SWS vanes and cathode. The electron distribution was observed to be axis-symmetric in each transverse cross section in the yz-plane at t= 65.72 ns as shown in Fig. 7. In order to observe the growth of the RF field, we set a number of electric field probes. The generation of RF power was monitored at the output port. The impedance discontinuity between the choke vanes and SWS vanes benefitted the MILO operation as the high impedance in the choke vane section resulted in lower E-field to avoid electrical breakdown and the low impedance in SWS vane section resulted in high spoke current. The higher spoke current due to more electrons at the interaction region enhanced the efficiency to ~ 25% as compared to the similar conventional MILOs that offer efficiencies of ~15% [16] and 12 % [10]. The E-field amplitude at the output port was obtained as 80 kV/m (Fig. 8). The RF output of ~ 6GW was observed (Fig. 9) at 3.1GHz in TM_{01}-fundamental mode of operation with beam current of 50 kA and beam voltage of 500 kV (Figs. 10 and 11). The Fourier transform of *E*-field amplitude shows the desired frequency of operation as 3.1 GHz as shown in Fig 12. The magnetic field distribution at the output port (Fig. 13) clearly indicates that the improved design operates in fundamental mode. The microwave frequency obtained from the simulation is 3.1 GHz against that of the cold π-mode frequency of 3.3 GHz. The shift in the simulated operating frequency is attributable to the beam loading effect. The energy distribution over the interaction length at t = 95 ns is shown in Fig. 14.

IV. EFFICIENCY ENHANCEMENT

The enhancement of overall efficiency was obtained by reducing the inner radius of choke vane, SWS vane, Extractor vane and Beam dump by 1mm. In addition to the above the position of stubs on the beam dump played vital role in matching the impedance at the output of MILO in order to extract maximum RF power. A part of the cathode extended into the Beam dump was reduced from 164.4mm to 7.4mm for maintaining the sufficient load length required to generate the critical current for generating the required self-magnetic field and also the reduced cathode length helped in preventing off axis shift due to cantilever force and thus asymmetric emission of electron beam is prevented. In view of the above, the overall efficiency of the Improved MILO is enhanced to 25% for the voltage of 500kV and current of 47.5kA.

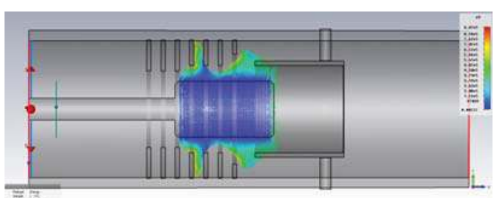

Fig. 7. Distribution of electrons at 65.72 ns

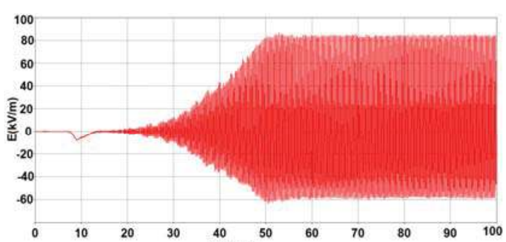

Fig. 8. Instantaneous E-field amplitude

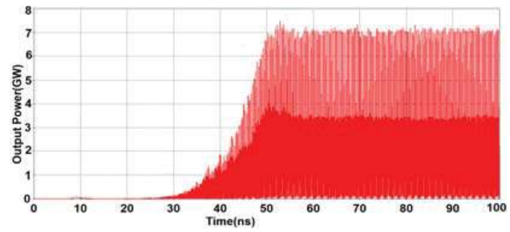

Fig. 9. Peak output power of improved MILO

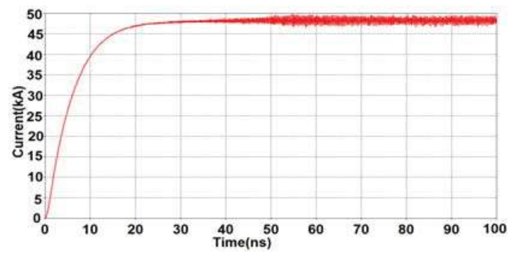

Fig. 10. Build-up of current with time

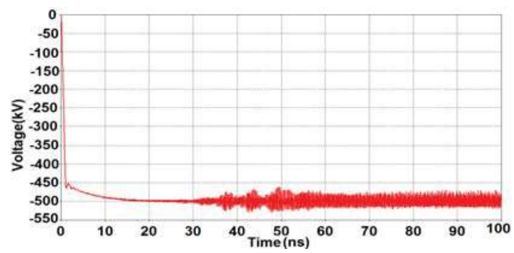

Fig. 11. Build-up of voltage with time

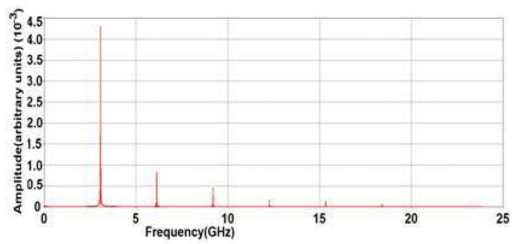

Fig. 12. Fourier transform of the electric field at the output port

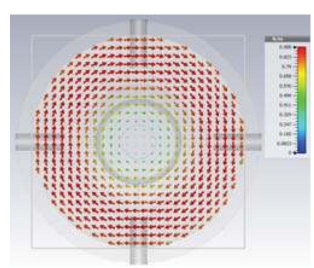

Fig. 13. The TM_{01} magnetic field distribution at the output port Schematic of coaxial disk loaded SWS

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.11, NO.5, SEPT 2016

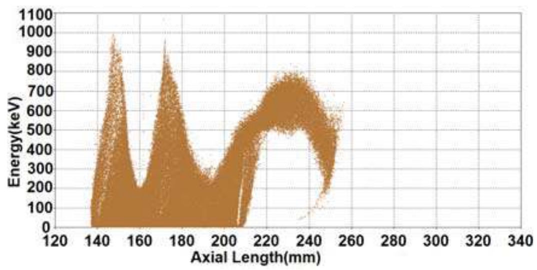

Fig. 14. Energy distribution against interaction length at 95 ns

V. CONCLUSION

An improved S-band MILO has been designed using analytical method, and optimized and simulated using 3-D electromagnetic PIC code. The total length of the MILO has been significantly reduced by ~ 22% as compared to the earlier conventional ones. A set of design parameters have been optimized for enhancement of conversion efficiency that includes reduction in length of cathode and beam dump, inner radii of choke and SWS vane, and placement of stubs. Reducing the length of cathode could manifest several advantages: (i) additional electrons are available for interaction with the desired operating mode for enhanced efficiency (ie.higher number of spoke electrons could participate in interaction), (ii) sufficient self-generation of magnetic field, and (iii) the reduced cathode length prevents cantilever axial shift and off-axis asymmetric emission of electron beam. The peak power of 6 GW and a frequency of 3.1 GHz at TM_{01}-mode with power conversion efficiency of ~25% has been achieved with the diode voltage of 500 kV and current of 47.5kA.

APPENDIX-A: VALIDATION

In order to validate the efficacy of the present analysis using CST Particle Studio, validation exercise has been carried out against a model of the device for which the details are available in the literature [16].

A comparison of the results are tabulated as shown in Table A.1. Typical simulated peak output power and Fourier Transform of the electric field at the output port of MILO [16] are shown in Figs.A.1 and A.2 respectively.

Table A.1: Comparison of Results for Validation

Parameters	Results	
	Simulation using MAGIC [16]	Simulation using CST Particle studio
Beam Voltage	500 kV	500 kV
Beam Power	23.5 GW	23.5GW
Frequency	2.44 GHz	2.48GHz
RF Output Power	2.5 GW	2.54 GW
Power Conversion Efficiency	10.6 %	10.8 %

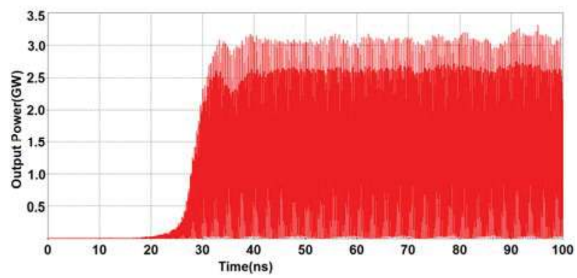

Fig. A.1 Peak output power of the MILO [16] obtained through CST simulation

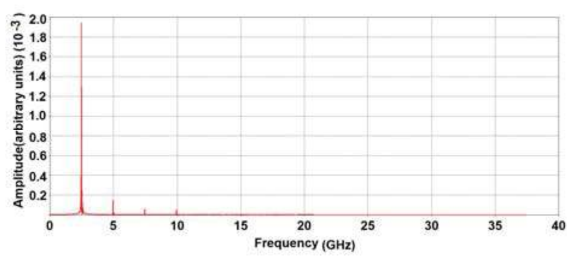

Fig. A.2 Fourier transform of the electric field at the output port of the MILO [16] obtained through CST simulation

REFERENCES

[1] R. W. Lemke and M. C. Clark, "Theory and simulation of high-power microwave generation in a magnetically insulated transmission line oscillator," *J. Appl. Phys*., vol. 62, no. 8, pp. 3436–3440, Oct. 1987.

[2] M. C. Clark, B. M. Marder, and L. D. Bacon, "Magnetically insulated transmission lines oscillator," *Appl. Phys. Lett*., vol. 52, no. 1, pp. 78–80, Jan. 1988.

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.11, NO.5, SEPT 2016

[3] B.M. Marder, "Simulated behavior of magnetically insulated oscillator," *J. Appl. Phys*., vol. 65, no. 3, pp. 1338–1349, Feb. 1989.

[4] R. W. Lemke, S. E. Calico, and M. C. Clark, "Investigation of a load- limited, magnetically Insulated transmission line oscillator (MILO)," *IEEE Trans. Plasma Sci*., vol. 25, no. 2, pp. 364-373, Apr. 1997.

[5] S. H. Gold and G. H. Nusinovich, "Review of high-power microwave source research," *Rev. Sci. Inst*., vol. 68, no. 11, pp. 3945–3974, Nov. 1997.

[6] D. H. Kim, H. C. Jung, S. H. Min, S. H. Shin, G. S. Park, D. W. Yim, and C. H. Kim, "Experimental investigation of giga-watts magnetically insulated transmission line oscillator (MILO)," in Proc. *IEEE Int. Vacuum Electron. Conf*., pp. 561–562, Sep. 2006.

[7] R. Cousin, J. Larour, P. Gouard, and P. Raymond, "Evidence of the 3π/4 interaction mode in a compact magnetically insulated line oscillator process," *J. Appl. Phys*., vol. 100, no. 8, pp. 084512-1–084512-5, Oct. 2006.

[8] Z. Q. Li, H. H. Zhong, Y. W. Fan, and T. Shu, "Investigation of a S-band tapered magnetically insulated transmission line oscillator," *Chin. Phys. Soc.*, vol. 26, no. 5, pp. 055201-1–055201-3, 2009.

[9] J. W. Eastwood, H. P. Hook, and H. C. Hakins, "The Tapered MILO," *IEEE Trans. Plasma Sci.*, vol. 26, no. 3, pp. 698–713, Jan. 1998.

[10] Fen Qin, Dong Wang, Dai-Bing Chen, and Jie Wen, "Simulation Investigation of S-Band Higher-Order-Mode Depressed MILO," *IEEE Trans. Plasma Sci.*, vol. 40, no. 7, pp. 1933–1936, July 2012.

[11] Yu-Wei Fan, Hui-Huang Zhong, Ting Shu, and Zhi-Qiang Li, "Theoretical investigation of the fundamental mode frequency of the magnetically insulated transmission line oscillator," *Physics of Plasmas* 15, 123504, 2008.

[12] Smrity Dwivedi, Pradeep Kumar Jain, "Design Expressions for the Magnetically Insulated Line Oscillator," *IEEE transactions on plasma science*, vol. 41, No. 5, pp.1549-1556, May 2013.

[13] H. C. Chen, "General Theory of the Diocotron Instability of a Relativistic Electron Beam," *Naval Surface Weapons Center, White Oak, Silver Spring*, MD,20903-5000.

[14] R. Cousin, Understanding the physical operating principles of a high power microwave source of the MILO-type, Ph.D. dissertation, *Plasma Phys. Section*, Ecole Polytechnique, Palaiseau, France, Apr. 2005.

[15] Parker, R.K, Explosive electron emission and the characteristics of high current electron flow, *Air Force Weapons Laboratory*, AFWL-TR-73-92, Kirtland Air force base, New Mexico, Feb., 1974.

[16] R. Cousin, J. Larour, J. Gardelle, B. Cassany, P. Modin, P. Gouard, and P. Raymond, "Gigawatt emission from a 2.4-GHz compact magnetically insulated line oscillator (MILO)," *IEEE Trans. Plasma Sci*., vol. 35, no. 5, pp. 1467–1474, Oct. 2007.

Journal of Electromagnetic Waves and Applications

From:	Journal of Electromagnetic Waves and Applications <onbehalfof+tewa-peerreview+tandf.co.uk@manuscriptcentral.com>
To:	<nallasamy@mtrdc.drdo.in>
Sent Date:	Fri 28 October 2016 [7:15:47 AM]
Received Date:	Fri 28 October 2016 [7:15:28 AM]

27-Oct-2016

TEWA-2016-0597.R1 - Electromagnetic Simulation and Experimental Characterization of RF Interaction Structure of an S-band S-Band Magnetically Insulated Line Oscillator

Dear Mr V Nallasamy,

Congratulations on having your paper accepted.

I am continuing to process your paper; however in order to proceed with the pre-publication processes of copy-editing and type-setting, I require the clean source file (without track changes, text colors, highlighting) for your main document as we cannot proceed with a PDF.

Source files may be provided in any standard editable format, including Word or LaTeX. Please ensure that all equations and tables are supplied in an editable format within the source files, not as embedded images. I would very much appreciate if you could use the equation option in MS Word when stating the formula instead of figure.

I would be very grateful if you could provide the source files for this submission as soon as possible so I can proceed with publication and avoid delay.

Thank you in advance and I look forward to hearing from you.

Best regards,

Ms Franchesca Del Rosario
Journal of Electromagnetic Waves and Applications

Printed using ConnectXF®

Electromagnetic Simulation and Experimental Characterization of RF Interaction Structure of an S-Band Magnetically Insulated Line Oscillator

V Nallasamy[*], C Narasimhamurthy[*], B Geetha[*], Sanjay Kumar Gupta[*], Subrata Kumar Datta[*], SUM Reddy[*] and P K Jain[**]

[*]Microwave Tube Research and Development Centre, Bangalore-560013, INDIA.
[**]Centre of Research in Microwave Tubes, Department of Electronics Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi-221005, INDIA.
Email: [*]nallasamy@mtrdc.drdo.in, [*]murthy@mtrdc.drdo.in, [*]bgeethamtrdc@rediffmail.com, [*]sanjay@mtrdc.drdo.in, [*]skd@ mtrdc.drdo.in, [*]reddy@mtrdc.drdo.in, [**]pkjain.ece@iitbhu.ac.in

Abstract: An S-band RF interaction structure of a Magnetically Insulated Line Oscillator (MILO) operating at fundamental-mode was designed using analytical formulations, and simulated using 3-D electromagnetic code CST Microwave Studio for its dispersion characteristics and RF output performance. The slow-wave structure was fabricated using precision CNC machining and characterized for its dispersion characteristics. The measured value of pi-mode frequency was found to be in close agreement (2.6%) with that from the simulation.

Index Terms- **Dispersion relation, Coaxial disc-loaded waveguide, Magnetically insulated line oscillator (MILO), Slow-wave structure.**

Corresponding Author:

V Nallasamy
Microwave Tube Research & Development Centre,
DRDO
Ministry of Defence, Government of India
Bharat Electronics Complex, Bangalore – 560013, India
Mail Id: nallasamy@mtrdc.drdo.in

I. INTRODUCTION

Magnetically Insulated Line Oscillator (MILO) invented by Lemke and Clark in 1987 [1] became a popular choice as a high-power microwave (HPM) source for military applications. Its unique magnetic self-insulating property enables the device to handle large output power of the order of tens to hundreds of GW at a modest applied voltage of several hundreds of kilovolts. Moreover, no requirement of externally applied DC magnetic field also facilitates compact and lightweight configuration of the device. A basic configuration of the MILO is shown in Fig. 1 comprising of three major subsystems: (i) Cathode, (ii) Slow-wave structure (SWS) as a part of anode, and (iii) Collector or beam dump. At high voltages, electrons are emitted from the cathode and the current carried by the body (anode) creates a sufficiently strong magnetic field such that these electrons cannot cross the interaction gap. The electrons drift axially in the crossed electric and self-generated magnetic fields. The slow-wave structure (SWS) facilitates the interaction between the axially drifting electrons (the region adjacent to the cathode) and the axially directed slow electromagnetic wave to generate microwaves. However, it suffers from the fundamental limitation of low RF conversion efficiency. This is due to the utilization of maximum load current for generating the self-magnetic field [1]-[2].

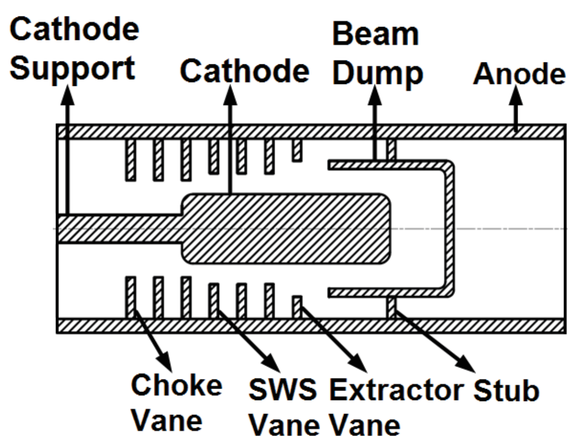

Fig.1. Schematic of Magnetically Insulated Line Oscillator

The first ever high-power MILO developed by Lemke *et al*. [3] could deliver output power of 2.1GW power at L-band having an efficiency of 10.3%. Cousin *et al*. developed a MILO with a 4-cavity slow-wave structure operating in $3\pi/4$ mode at a beam voltage of 600 kV [4], for which the dispersion characteristics were obtained through simulation in 3D electromagnetic code MAGIC. In 2007, Dong Wang *et al*. [5] investigated the dispersion relation of coaxial disc-loaded SWS for symmetric and asymmetric modes using field matching approach. Yu-Wei Fan *et al.* [6] used equivalent circuit analysis for obtaining the fundamental-mode frequency of MILO. Recently, Nallasamy *et al*., [7] simulated an improved S-band MILO using CST Microwave Studio (efficiency enhanced to 25%) operating at the beam voltage of 500kV and current of 47.5kA.

Estimation of the fundamental frequency is a pre-requisite for designing the RF interaction structure (Fig. 2) of a MILO. For a cavity depth of d, the fundamental-mode frequency (f) can be approximately estimated as $f = c/4d$, with c is the velocity of electromagnetic wave in free space. However, to the best of the knowledge of the present authors, there is no exact expression for accurate estimation of the fundamental-mode frequency other than field-analysis or 3D electromagnetic simulation. Field-analysis and/or 3D electromagnetic simulation invariably requires verification through cold-test measurements, as the analyses always have some approximations and assumptions.

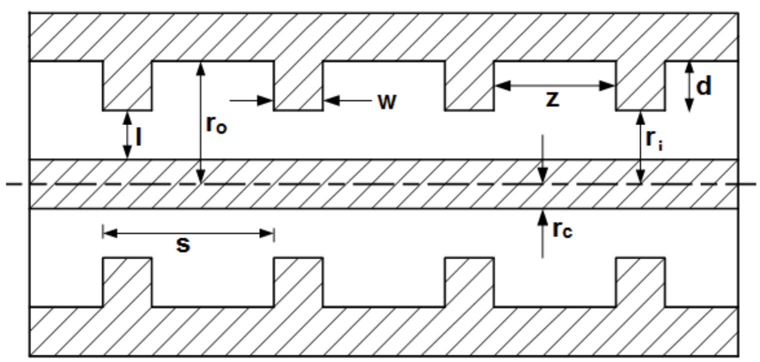

Fig. 2 Schematic of coaxial disc-loaded SWS.

In this paper, we present the design and simulation of the RF interaction structure of an S-band MILO. The design was carried out using analytical formulations and was simulated using 3D electromagnetic code CST Microwave Studio for obtaining the dispersion characteristics for the fundamental-mode operation. The RF interaction structure was fabricated with aluminum material and cold-test measurements were carried out for evaluating the dispersion characteristics. The paper is organized as follows: Design of the RF interaction structure is presented in Section-II and dispersion characteristics of the MILO by simulation and cold-test measurement are presented in Section III followed by the conclusion in Section IV.

II. DESIGN OF RF INTERACTION STRUCTURE

We have considered a MILO with the slow-wave structure comprising periodically spaced cavities formed by placing concentric circular discs with apertures in a smooth waveguide, as shown in Fig. 2. The slow-wave structure supports number of slow-wave modes. Here, r_o and r_i are the outer and inner radii of the SWS vanes; $d(= r_o - r_i)$ is the cavity depth; w is the thickness of the SWS vane; $z(=s-w)$ is the distance between the SWS apertures; r_c is the cathode radius; s is the circuit periodicity; and $l=r_i-r_c$ is the free space gap between anode to cathode.

As the cathode current reaches beyond the critical current, the self-magnetic field generated therein confines the electrons and prevents them reaching upto the anode. The electrons derive equipotential surfaces and move perpendicular to the crossed electric and magnetic fields. The minimum current or critical current I_{cr} required to insulate the beam is defined as [8]:

$$I_{cr} = \frac{4\pi m_0 c^3 \varepsilon_0 \sqrt{\gamma_0^{\,2}-1}}{e \ln(r_a/r_c)} = \frac{I_0 \sqrt{\gamma_0^{\,2}-1}}{2\ln(r_a/r_c)} \tag{1}$$

where, $I_0 = (4\pi m_0 c^3 \varepsilon_0)/e$ is the starting current for oscillation, e is the electron charge, m_0 is the electron mass at rest, and $\gamma_0\,(=1+eV_0/m_0c^2)$ is the relativistic mass factor with V_0 as the beam voltage. Under the condition of the insulated electron flow filling the anode-to-cathode gap, the total anode current or the para-potential current (I_p) becomes [8]:

$$I_p = \frac{I_0\,\gamma_o \ln\left(\gamma_0 + \sqrt{\gamma_o^2 - 1}\right)}{2\ln\left(r_i/r_c\right)} \tag{2}$$

At the prevailing condition of Diocotron instability [9], some of the electrons of the beam reach the anode and some others remain at the magnetic cutoff, while the other electrons migrate towards the anode by forming bunches or spokes. The mode of oscillation of MILO is established when electron drift velocity is slightly greater than the phase velocity of the RF wave. The condition of synchronism is given as [10]:

$$v_d = \frac{E_0}{B_0} = \frac{V_0}{2\ln\left(r_i/r_c\right)}\left(\frac{2\pi r}{\mu_0 I_t}\right) = \frac{2\pi\varepsilon_0 c^2}{\ln\left(r_i/r_c\right)}\left(\frac{V_0}{I_t}\right) \cong 0.3c \tag{3}$$

Here, v_d is the electron drift velocity, ε_0 is the permittivity of free-space and I_t is the total anode current. The RF phase velocity (v_ϕ) at under the condition of synchronism ($v_\phi \cong v_d$) can be expressed as [10]:

$$v_{\varphi} = \frac{s}{2d/\mathrm{c}} \cong 0.3c = \frac{\omega}{\beta_0} = \frac{2\pi f}{(\pi/s)} = 2\,s\,f \tag{4}$$

Here, ω is the angular frequency and β_0 is the axial propagation constant. At the beam voltage of 500kV and impedance of 25 **Ω**, the ratio of the inner radius of the anode to the cathode radius is given by [10]:

$$\frac{r_i}{r_c} = 1.6 \tag{5}$$

The design starts with the inputs: the operating frequency (f), beam voltage (V_0), cathode radius (r_c) and the width of the SWS vane (w) is chosen with practical considerations [3], [7], [10]. The values of the circuit periodicity (s) and cavity depth (d), are arrived at using the condition of synchronism ($v_{\phi} \cong v_d$) and the expressions (3) and (4) with the known value of operating frequency (f). The expressions (1) and (2) are used with the known value of beam voltage (V_0) and (r_i / r_c) from (5) to arrive at the critical current for self-magnetic insulation and total current in the device for sustainable oscillation. The value of inner radius of the SWS vane (r_i) is directly calculated using (5); and the value of outer radius of the SWS (r_0), interaction gap (z) and the free space gap between anode to cathode (l) are obtained from the relations, $r_0 = r_i + d$, $z = s - w$ and $l = r_i - r_c$, respectively. The dimensions of the slow-wave structure thus arrived at are: r_c = 25 mm; r_i = 40 mm; r_0 = 61.4 mm; s = 13 mm; d = 21.4 mm; w = 4 mm; z =9 mm; and l =15 mm.

III. SIMULATION AND COLD-TEST MEASUREMENT

The present RF interaction structure consists of 4 cavities (3 full cavities and 2 half cavities) along with two co-axial probes of 50Ω impedance with SMA-type connectors. The structure has been modeled along with the cathode with one probe as the input port and the other probe as the output port. The 3D modeling of the device was carried out using CST Studio with adaptive mesh refinement. The 3D model of the RF interaction structure with short-length cathode and probes is shown in Fig.3. SWS vanes, cathode, anode, and probes of MILO structure have been modeled using a perfect electric conductor (PEC) with background as vacuum. The MILO structure has been modeled and simulated in the linear co-ordinate system with hexahedral meshing using the time domain solver module of CST microwave studio. The time domain analysis confirms the π-mode of operation at 3.7 GHz. The return loss versus frequency and the dispersion characteristics as obtained from the simulation are shown in Fig. 4 and Fig. 5, respectively.

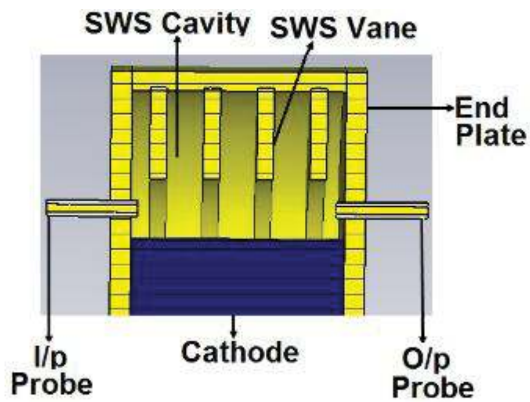

Fig. 3 Cut view of the RF interaction structure along with the cathode and the coupling probes

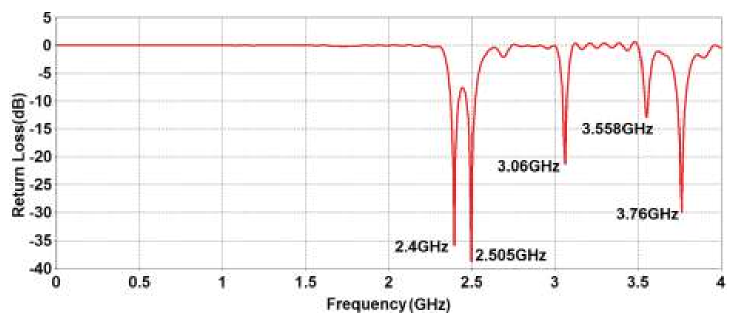

Fig. 4 S_{11} plot of the RF interaction structure against frequency

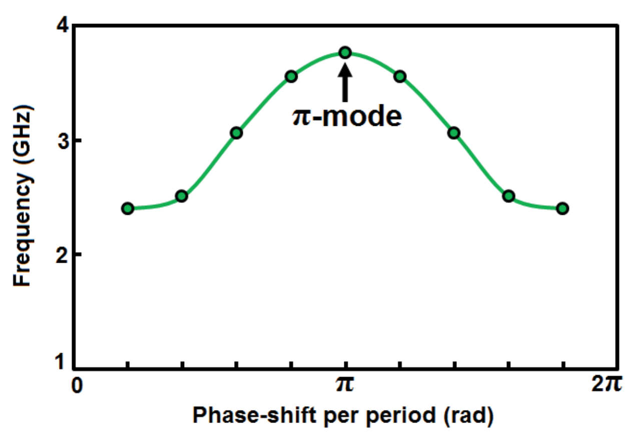

Fig. 5 Dispersion characteristics of the RF interaction structure

Subsequent to the design and simulation, the RF interaction structure was developed with SMA-type input and output couplers. RF signal (0 dBm) was fed from a Network Analyzer to the cavity through one port with the other port of the cavity terminated to a matched load as shown in Fig. 6. The return loss profile of the structure as obtained in the Network Analyzer is shown in Fig. 8.

It may be noted from the cold test measurement that 5 resonant frequencies are observed in the return loss profile: 2.4 GHz, 2.505 GHz, 3.06 GHz, 3.558 GHz, and 3.76 GHz. These frequencies are interpreted to obtain the dispersion characteristics as compared against simulation in Fig. 9. The measured pi-mode frequency was found to be 3.86 GHz against the simulated value of 3.76 GHz (deviation of around 2.6% with regard to simulation). The shift in simulated π-mode frequency from the design frequency of 3.3 GHz is due to the insertion of probes on both sides of the RF interaction structure caused the perturbation of electric field inside the RF interaction structure. The deviation in measured π-mode frequency is mainly due to the fabricational tolerances and the corner radius in the experimental cavity along with perturbation of electric field caused by the insertion of probes on both sides of the RF interaction structure.

Fig. 6 Fabricated RF interaction structure

Fig. 7 Components of the RF interaction structure

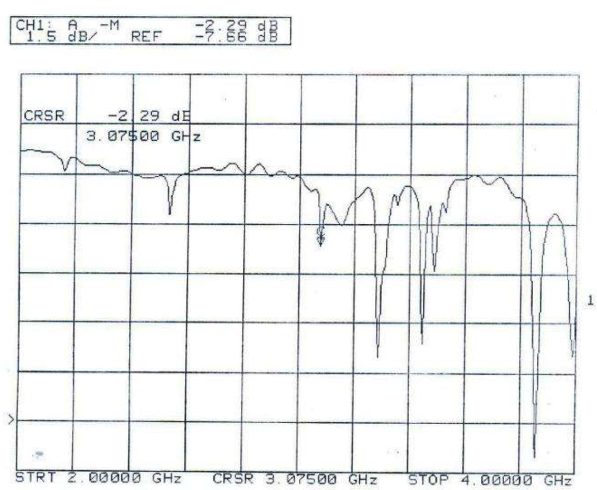

Fig. 8 Measured S_{11} performance of the RF interaction structure

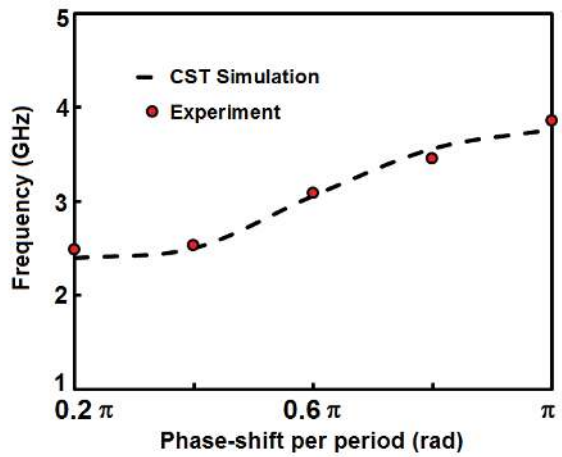

Fig. 9 Comparison of simulation and cold-test measurement

IV. CONCLUSION

The RF interaction structure of an experimental S-band MILO, with single-shot output power of around 2.5 GW, has been designed and the beam absent (cold) electromagnetic simulation, has been carried out using CST Microwave Studio by inserting probes ion both sides of RF interaction structure. Based on the design and cold simulation, the assembly and piece parts have been fabricated and assembled for cold test measurements using scalar network analyzer (SNA) based on resonant perturbation method. Comparing with the design π-mode frequency of 3.3 GHz, the change in cold simulated π-mode frequency is due to the perturbation of electric field by the insertion of probes on both sides of the RF interaction structure. The deviation in measured π-mode frequency against the design and simulated π-mode frequency is mainly due to the fabricational tolerances along with perturbation of electric field caused by the insertion of probes. The measured results are validated against the simulated results of design π-mode frequency. The results obtained from both simulation and measurement are in close agreement, showing the efficacy of the design.

ACKNOWLEDGEMENT

Authors are thankful to the Director, MTRDC for kind support to carry out the work and necessary permission to publish the work.

REFERENCES

[1] R. W. Lemke, and M. C. Clark, "Theory and simulation of high-power microwave generation in a magnetically insulated transmission line oscillator," *J. Appl. Phys*., vol. 62, no. 8, pp. 3436–3440, Oct. 1987.

[2] M. C. Clark, B. M. Marder, and L. D. Bacon, "Magnetically insulated transmission lines oscillator," *Appl. Phys. Lett*., vol. 52, no. 1, pp. 78–80, Jan. 1988.

[3] R. W. Lemke, S. E. Calico, and M. C. Clark, "Investigation of a load-limited, magnetically insulated transmission line oscillator (MILO)," *IEEE Trans. Plasma Sci*., vol. 25, pp. 364-374, 1997.

[4] R. Cousin, J. Larour, P. Gouard, and P. Raymond, "Evidence of the 3π/4 interaction mode in a compact magnetically insulated line oscillator process," *J. Appl. Phys*., vol. 100, no. 8, pp. 084512-1–084512-5, Oct. 2006.

[5] D. Wang, Z. K. Fan, D. B. Chen, and J. Deng, "Investigation of dispersion characteristics in coaxial disc-loaded slow wave structures with both symmetric and asymmetric modes", *IEEE Trans. Plasma Sci*., vol. 35, pp. 1070-1074, 2007.

[6] Y. W. Fan, H. H. Zhong, T. Shu, and Z. Q. Li, "Theoretical investigation of the fundamental mode frequency of the magnetically insulated transmission line oscillator," *Physics of Plasmas*, vol. 15, pp. 123504(1-5), 2008.

[7] V. Nallasamy, S. K. Datta, S. U. M. Reddy, and P. K. Jain, "Efficiency enhancement of an S-band magnetically insulated line oscillator,"*International Journal of Microwave and Optical Technology*, vol.11, No.5, pp. 324-331, Sept 2016.

[8] S. Dwivedi, P. K. Jain, "Design expressions for the magnetically insulated line oscillator," *IEEE Transactions on Plasma Science*, vol. 41, No. 5, pp.1549-1556, May 2013.

[9] H. C. Chen, "General theory of the Diocotron instability of a relativistic electron beam," *IEEE Trans. Nuclear Sci*., vol. 32, pp. 2380-2382, 1985.

[10] R. Cousin, "Understanding the Physical Operating Principles of a High Power Microwave Source of the MILO-type," Ph.D. dissertation*, Plasma Phys. Section*, Ecole Polytechnique, France, Apr. 2005.

BIO-DATA

V. Nallasamy
Scientist-F
Microwave Tube Research and Development Centre (MTRDC)
Defence Research and Development Organization (DRDO)
Ministry of Defence
BE Complex
Jalahalli (Post)
Bengaluru-560 013, INDIA
Email:nallasamy@mtrdc.drdo.in

V Nallasamy was born in Thummakkundu, Madurai (Tamilnadu), India in 1974. He received his B.E in Electronics and Communication Engineering from Thiagarajar College of Engineering, Madurai, Tamilnadu during 1995. He has joined MTRDC, DRDO as a Scientist-'B' in July 1996 and also working for his Ph.D. degree in Electronics Engineering at Indian Institute of Technology (Banaras Hindu University), Varanasi, India.

He has authored or coauthored over 3 research papers in international/national journals/conference proceedings. His research interest includes High Power Traveling Wave Tubes, High Power Microwave Sources and Microwave Computer-Aided Engineering.

Signature of the Candidate