CHAPTER 5

PERFORMANCE IMPROVEMENT OF THE GYROKLYSTRON AMPLIFIERS USING STAGGER-TUNING TECHNIQUE

5.1 Introduction

Wideband gyro-amplifiers have potential applications in millimeter-wave high-resolution radar and high- density, high-directivity communication systems [Gilmour (1986), Barker *et al.* (2001), Thumm (2012)]. One of the major limitations of gyroklystron amplifier is its limited bandwidth operation. Unlike a gyro-TWT, which uses a non-resonant propagating structure, a gyroklystron uses resonant cavities similar to that in a conventional klystron for localized and intensified beam-wave interaction that yields higher powers and efficiencies. The bandwidth of the gyroklystron is limited to ~1% by the quality factor (~100) of the resonator. Thus, gyroklystrons provide high-gain amplification of electromagnetic waves with limited bandwidth [Choi 1998, Nusinovich 2004].

To increase the bandwidth of a gyroklystron, one can go for the cavity design similar to that in conventional klystrons, for example, the frequency-tunable first cavity, and a number of cavities with slightly different eigenfrequencies placed between the input and the output cavities. This method is known as the stagger-tuning and widely used to enhance the klystron bandwidth though at the cost of its gain. This technique of stagger-tuning can also be applied to broadband the gyroklystron. The use of so-called clustered cavities in gyroklystrons can also be employed for improving both efficiency and bandwidth of these devices. The concept of clustered cavities was at first suggested by R. Symons in the year 1994 for conventional klystrons for improving their bandwidth characteristics [Symons *et al.* (1994)]. In case of a clustered cavity gyroklystrons, each cavity is replaced by a bunch of doublets or triplets the quality factor of the cavity reduces to a factor according to the multiplet used in a bunch, but the overall dimension of the tube remains same. This technique helps us to increase the bandwidth of the device without affecting the gain and efficiency of the device. However, this technique increases the difficulty in the actual realization of the device due to problems occurring during the practical fabrication of the device having such complex cavities [Nusinovich *et al.* (1997), (2002)].

Here, in the present chapter, Chapter 5, the effect of stagger-tuning on the operation of gyroklystron amplifier designed in the previous chapter, Chapter 4 has been studied for its performance improvement. In general, the stagger-tuning increases the bandwidth and simultaneously decreases the gain of the devices. Therefore, the tradeoff in gain-bandwidth product needs to be analyzed in detail for the optimum performance of the device. Since, gain-bandwidth product is one of the important parameters for characterizing the performance of an amplifier. Thereby, in the present chapter, the effect of stagger-tuning on the gain-bandwidth product of the designed gyroklystron amplifier has been studied in detail.

The effect of stagger-tuning on the performance of gyroklystrons has been reported in the literature by many authors. In the year 1988, Chu *et al.* studied the effect of frequency detuning in the second and third cavities on the gain and efficiency of the four-cavity gyroklystron amplifier. Zasypkin *et al.* in the year 1995 reported the effect of penultimate cavity position and frequency detuning on the efficiency and gain of three-cavity gyroklystron amplifier. In the year 1997, Nusinovich *et al.* presented the generalized analytical theory for the stagger-tuned gyroklystrons based on the linear and nonlinear theories of gyroklystron amplifiers [Chu *et al.* (1988), Zasypkin *et al.* (1995), Nusinovich *et al.* (1997)].

In the present work, the same generalized theory has been extended for the performance improvement of our designed four-cavity gyroklystron amplifier. Here, we have used a technique by which the device gain can be expressed as the difference of two terms in which the first term is gain constant and independent of frequency detuning. The second term is dependent on frequency detuning and thus provides gain variation. This variable part is responsible for the stagger-tuning in gyroklystrons. Here, we optimize this variable gain term simultaneously for the gain and bandwidth in terms of normalized frequency detuning parameter. As a first step, the generalized results for four-cavity stagger-tuned gyroklystrons were obtained and validated against the reported results of Nusinovich *et al.* (1997). In the second step, the effect of stagger-tuning on the designed gyroklystron amplifier has been analyzed and validated through the results obtained from PIC simulation using 3D 'MAGIC' code.

5.2 Formalism

The equations of motion for weakly relativistic electrons in each cavity of gyroklystron, under the assumption of no space charge effect and zero velocity spread can be described by the following two interdependent expressions in terms of momentum (*p*), phase (θ) and distance (ς) in the normalized form as described in Chapter 2 [Tran *et al.* (1986)]

$$\frac{dp}{d\varsigma} = p^{s-1} Re\left(Ff(\varsigma)e^{is\theta}\right) \quad , \tag{5.1}$$

$$\frac{d\theta}{d\varsigma} - \Delta + 1 - p^2 = p^{s-2} Re(iFf(\varsigma)e^{is\theta}) \quad . \tag{5.2}$$

Here $p = p_\perp / p_{\perp 0}$ is the normalized electron momentum, θ is the electron phase $\varsigma = \left(\beta_{\perp 0}^2 / 2\beta_{\|0}\right)(\omega_0 z / c)$ is the normalized axial coordinate, and $\Delta = \left(2/\beta_{\perp 0}^2\right)(1 - s\omega_{c0}/\omega)$ is the normalized frequency detuning parameter arises due to CRM instability. The function $f(\varsigma)$ in the above two equations describes the nature of cavity field in the axial direction and F is its normalized amplitude defined as $F = \left(E_0 \beta_{\perp 0}^{s-4} / B_0 c\right)\left(s^{s-1} / 2^{s-1} n!\right) J_{m\pm s}(k_\perp r_b)$.

The susceptibility χ is the quantity which determines the interaction of electron beam with the cavity mode and it is defined as [Nusinovich (2004)]:

$$\chi = \frac{-i\sigma}{\omega} \quad , \tag{5.3}$$

where σ is the medium conductivity. This susceptibility can be calculated after solving equations (1) and (2) as [Gaponov *et al.* (1967), Nusinovich *et al.* (1997)]:

$$\chi = -\frac{2i}{F}\int_0^{\mu} f^*\left(\frac{1}{2\pi}\int_0^{2\pi}(pe^{-i\theta})^s d\theta_0\right) d\varsigma \quad . \tag{5.4}$$

Here, μ is the normalized length of the cavity and θ_0 is the initial phase of the electrons equally distributed at the entrance of the first cavity from 0 to 2π.

The balanced equation used here for obtaining the amplitude and phase of the cavity field as $F = |F_1| e^{i\psi_1}$ for the input cavity are:

$$|F_1|^2 = \frac{A^2}{(1 - I_{01}\chi'')^2 + (\delta_1 + I_{01}\chi')^2} \quad , \tag{5.5}$$

$$\tan\psi_1 = \frac{\delta_1 + I_{01}\chi'}{1 - I_{01}\chi''} \quad , \tag{5.6}$$

where χ' and χ'' are the real and imaginary part of the susceptibility (χ). A^2 is the intensity of the signal in the input cavity which is related to the driver power as:

$$A^2 = 4I_{01}\frac{P_{in}Q_{1,T}}{P_b Q_{cpl}} \quad . \tag{5.7}$$

Here I_{01} is the normalized beam current parameter for the input cavity, $Q_{1,T}$ is the total quality factor and Q_{cpl} is the coupling quality factor of the input cavity. P_{in} is the driver power and P_b is the electron beam power associated with the electron gyration. As there is no input for other cavities, the balance equation for them can be expressed as [Nusinovich (2004)]:

$$I_0\chi'' = 1 \quad , \tag{5.8}$$

$$I_0\chi' = -\delta \quad , \tag{5.9}$$

Here, δ is the normalized frequency detuning between the central operating frequency of the device and the cold resonant frequency of that particular cavity, $\delta = (\omega - \omega_s)/(\omega/2Q)$. Here Q is the loaded quality factor of the cavity. With the help of the above balance equation, the gain of the gyroklystron can be simply written as:

$$G(dB) = 10\log\left(\frac{|F_N|^2}{A^2}\right) \quad . \tag{5.10}$$

For the case of multicavity gyroklystrons, it is better to write this ratio of field intensities as the products of ratios characterizing the gain in each stage as:

$$\frac{|F_N|^2}{|F_{N-1}|^2}\frac{|F_{N-1}|^2}{|F_{N-2}|^2}\cdots\frac{|F_1|^2}{A^2} \quad . \tag{5.11}$$

Here, each ratio in the above chain can be expressed in terms of the balance equations discussed in equations (5.8) and (5.9). Correspondingly, the gain can be expressed as the sum of the gains in all stages. Since, we are studying the stagger-tuning in which δ_i can be different for each cavity, therefore we can calculate the bandwidth in terms of normalized frequency detuning.

5.3 Stagger-Tuned Four-Cavity Gyroklystron Amplifier

For studying the effect of stagger-tuning on the gyroklystron amplifier, the gain of the device can be expressed as the difference of two terms in which the first term is gain constant and independent of frequency detuning. The second term is dependent on frequency detuning and thus provides gain variation. This variable part is responsible for the stagger-tuning in gyroklystrons.

$$G = G^{(const)} - G^{(var.)} \quad . \tag{5.12}$$

Here the first term, is independent of frequency detuning, while the second term is the variable part of the gain, and it depends on frequency detuning. Mathematically, these terms can be expressed as [Nusinovich *et al.* (1997)]:

$$G^{const.} = 20 log\left\{\frac{8I_{02}I_{03}I_{04}\mu_{\Sigma}^{3}}{(1+I_{01})(1+I_{02})(1+I_{03})(1+I_{04})}\right\} \quad , \tag{5.13}$$

$$G^{\mathrm{var.}} = 10 log\left\{(1+\delta_1^2)(1+\delta_2^2)(1+\delta_3^2)(1+\delta_4^2)\right\} \quad . \tag{5.14}$$

The expressions for $G^{(const.)}$ and $G^{(var.)}$ are normalized in such a way that when frequency detuning in all the cavities become zero ($\delta_i \to 0$), the variable term vanishes. Hence, the device gain becomes maximum and its value is given by equation (5.13). To analyze further, let us consider the case where eigenfrequencies of the cavities modes form a non-equidistant spectrum, such that, $\omega_4 - \omega_3 = \omega_2 - \omega_1 \neq \omega_3 - \omega_2$ and also the quality factors (Q) of cavities are equal. Now, defining $\omega_0 = \frac{(\omega_2+\omega_3)}{2} = \frac{(\omega_1+\omega_4)}{2}$ and the two stagger-tuning parameters $\xi_1 = 2Q\frac{(\omega_0-\omega_1)}{\omega_0(1+I_0)}$ and $\xi_2 = 2Q\frac{(\omega_0-\omega_2)}{\omega_0(1+I_0)}$ the equation (5.14) can be written as:

$$G^{(\mathrm{var.})} = 10log\left\{\left[\left(1+\delta^2+\xi_1^{\,2}\right)^2 - 4\xi_1^{\,2}\delta^2\right]\left[\left(1+\overline{Q}\delta^2+\overline{Q}\xi_2^{\,2}\right)^2 - 4\overline{Q}\xi_2^{\,2}\delta^2\right]\right\} \quad . \qquad (5.15)$$

Here, $\overline{Q} = (1+I_0)^2\,\widetilde{Q}/\left(1+\widetilde{Q}I_0\right)^2$ where, $\widetilde{Q} = Q_1/Q_2 = Q_1/Q_3 = Q_1/Q_4$. Q_1, Q_2, Q_3, and Q_4 are the quality factor of first, second, third, and fourth cavity, respectively. As a simplest case, let us consider the case when eigenfrequencies of the cavities' modes form an equidistant spectrum, i.e., $\xi_1 = \xi_2 = \xi$. For such a case the equation (5.15) can be written as:

$$G^{(\mathrm{var.})} = 10log\left\{\left[\left(1+\delta^2+\xi^2\right)^2 - 4\xi^2\delta^2\right]\left[\left(1+\overline{Q}\delta^2+\overline{Q}\xi^2\right)^2 - 4\overline{Q}\xi^2\delta^2\right]\right\} \quad . \qquad (5.16)$$

The bandwidth of the gyroklystron can be determined using equation (5.16) and can be written as [Nusinovich (2004)]:

$$BW_0(\xi=0) = \left[\sqrt{2}-1\right]^{\frac{1}{2}}(1+I_0)/Q_4 \quad , \qquad (5.17)$$

$$BW(\xi) = \left[\xi^2 - 1 + \sqrt{2\left(1+\xi^2\right)}\right]^{\frac{1}{2}}(1+I_0)/Q_4 \quad . \qquad (5.18)$$

For $\xi^2 \le 1$, and

$$BW(\xi) = \left[\xi^2 - 1 + 2\sqrt{\xi^2}\right]^{\frac{1}{2}}(1+I_0)/Q_4 \quad , \qquad (5.19)$$

for $\xi^2 \ge 1$. The ratio of the gain-bandwidth product in the presence of stagger-tuning to that its absence is given by:

$$\Phi = \frac{BW(\xi)G(\xi)}{BW_0G_0} = \frac{BW(\xi)}{BW_0}\left[1 - \frac{\Delta G}{G_0}\right] \quad , \qquad (5.20)$$

where, $\dfrac{BW(\xi)}{BW_0}$ is the normalized bandwidth, ΔG is the variable gain ($G^{\text{var.}}$) and $G_0 = G^{const.}$. The flow chart shown in Fig. 5.1 illustrates the step by step procedure to study the effect of stagger-tuning on a gyroklystron amplifier.

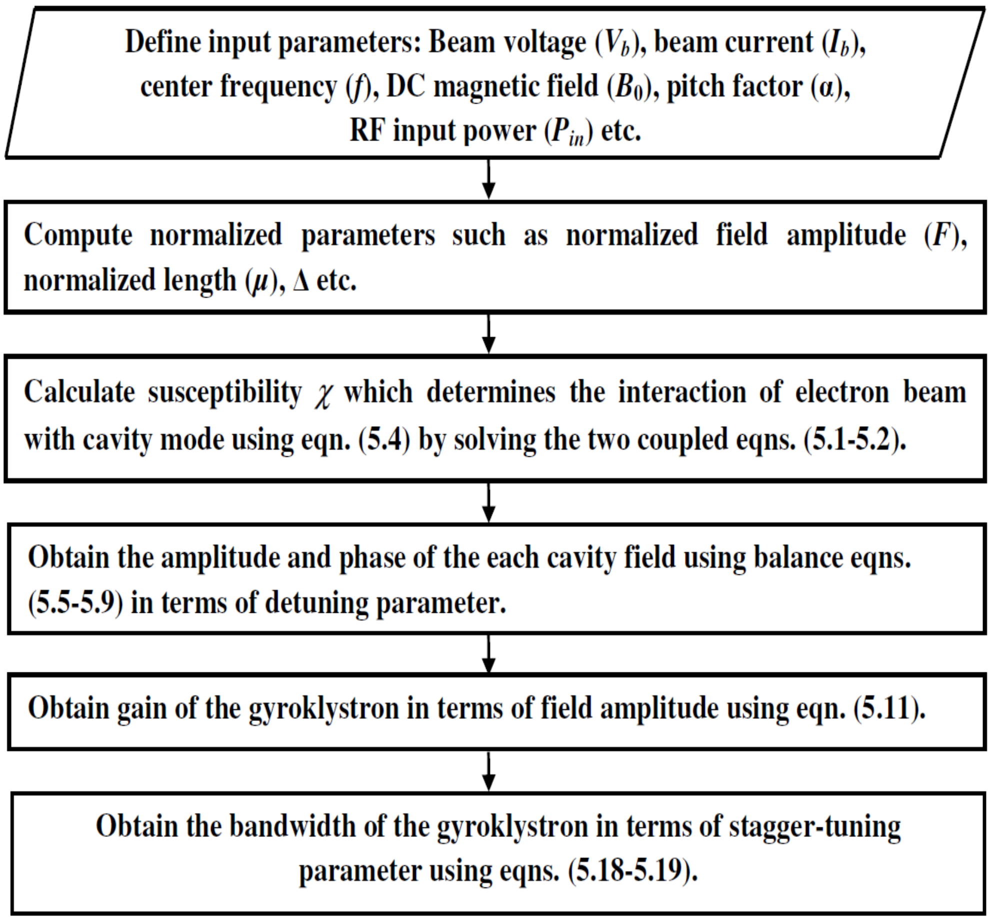
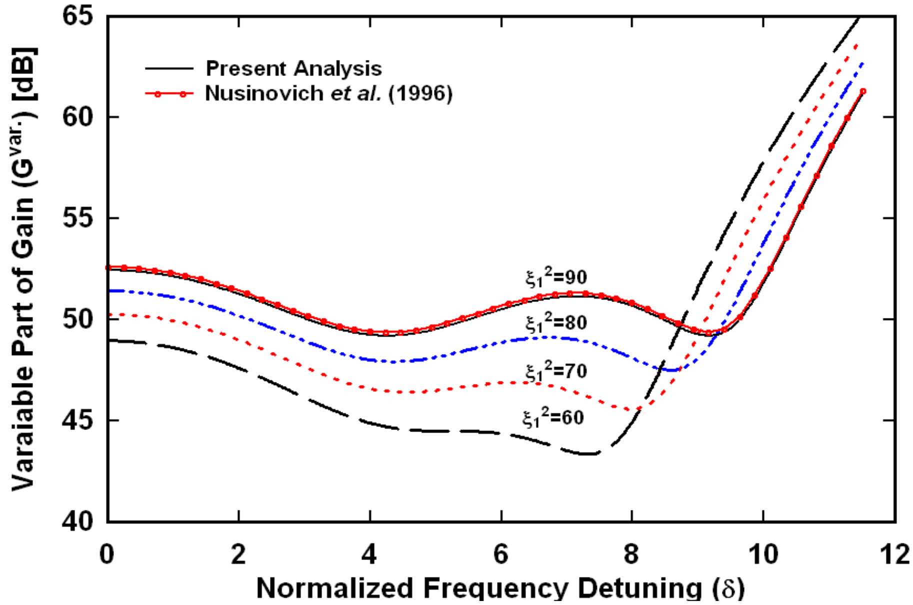
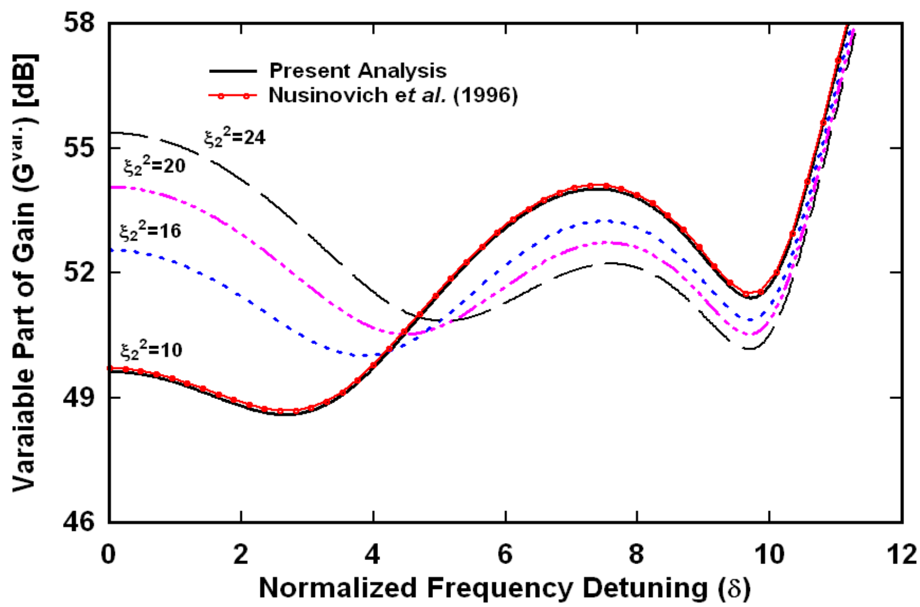


Fig. 5.1 Flow chart illustrating the steps involved in the calculation of the bandwidth of a stagger-tuned gyroklystron amplifier.

The dependence of variable gain on frequency detuning parameter has been studied by using equation (5.15). As an example, the equation (5.15) has been analyzed for $\overline{Q}$ = 0.2 and several values of stagger-tuning parameter. Figure 5.2 shows the dependencies of variable part of gain on frequency detuning (δ) for $\overline{Q}$ = 0.2 and (a) $\xi_2^{\,2} = 18$ and different values of $\xi_1^{\,2}$, (b) $\xi_1^{\,2} = 100$ and different values of $\xi_2^{\,2}$. For the validation purpose, the results obtained here for a particular case are compared with the earlier reported results of Nusinovich *et al.* (1997). It can be seen from the Fig. 5.2 that the results obtained from both the approaches are in agreement within ~ 2%.



(a)



(b)

Fig. 5.2 Variable part of gain as the function normalized frequency detuning (δ) of the cavities for $\overline{Q}$=0.2 and (a) $\xi_2^{\,2}=18$ and different values of $\xi_1^{\,2}$, (b) $\xi_1^{\,2}=100$ and different values of $\xi_2^{\,2}$.

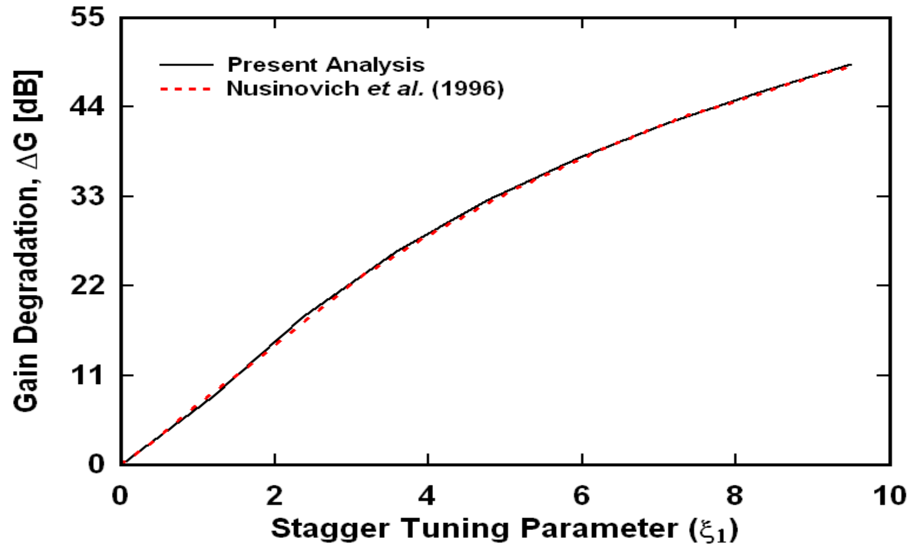


Fig. 5.3 Gain degradation as a function of stagger-tuning parameter ξ_1 for $\overline{Q}$=0.2 and $\xi_2^{\,2} = 0.2\xi_1^{\,2}$.

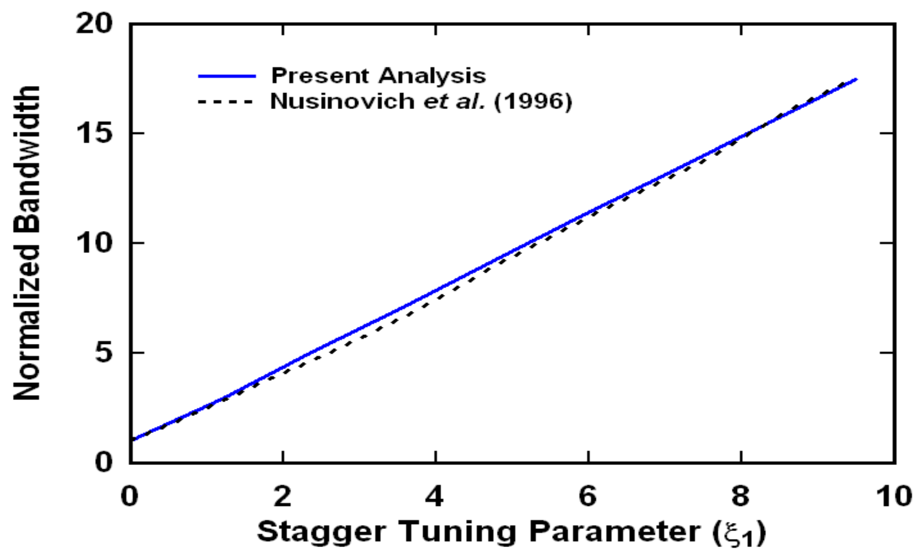


Fig. 5.4 Normalized bandwidth as a function of stagger-tuning parameter ξ_1 for $\overline{Q}$=0.2 and $\xi_2^{\,2} = 0.2\xi_1^{\,2}$.

Fig. 5.3 shows the variation of gain degradation of four cavity stagger-tuned gyroklystron as the function of stagger-tuning parameter (ξ_1) for $\overline{Q}$ = 0.2 and $\xi_2^{\,2} = 0.2\xi_1^{\,2}$. It is quite obvious and confirmed by the Fig. 5.3 that the gain degradtion increases with stagger-tuning parameter while the overall gain of the device decreases as $G = G^{(const)} - G^{(var.)}$ due to frequency mismatch between the cavities of the gyroklystrton amplifier. The maximum gain degradation for the four cavity stagger-tuned gyroklystron is obtained around 48 dB for the stagger-tuning parameter (ξ_1) equal to 9.5. The results obtained here are validated against the reported results of Nusinovich *et al.* (1997).

Fig. 5.4 shows the variation of normalized bandwidth of four cavity stagger-tuned gyroklystron as the function of stagger-tuning parameter (ξ_1) for $\overline{Q}$ = 0.2 and $\xi_2^2 = 0.2\xi_1^2$. It can be seen from Fig. 5.4 that the normalized bandwidth of the four–cavity gyroklystron amplifier increases upto 9.5 times as compared to the four-cavity gyroklystron amplifier without stagger-tuning for stagger-tuning parameter (ξ_1) equal to 9.5. However, such enhancement of bandwidth occurs at large values of ξ where device operation is not practical because of substantial gain loss caused by stagger-tuning as discussed above. Therefore, the choice of stagger-tuning for the device should be determined as a result of a trade-off between the gain and bandwidth. Hence, the appropriate stagger-tuning parameter for the gyroklystron should be chosen on the basis of its maximum gain-bandwidth product.

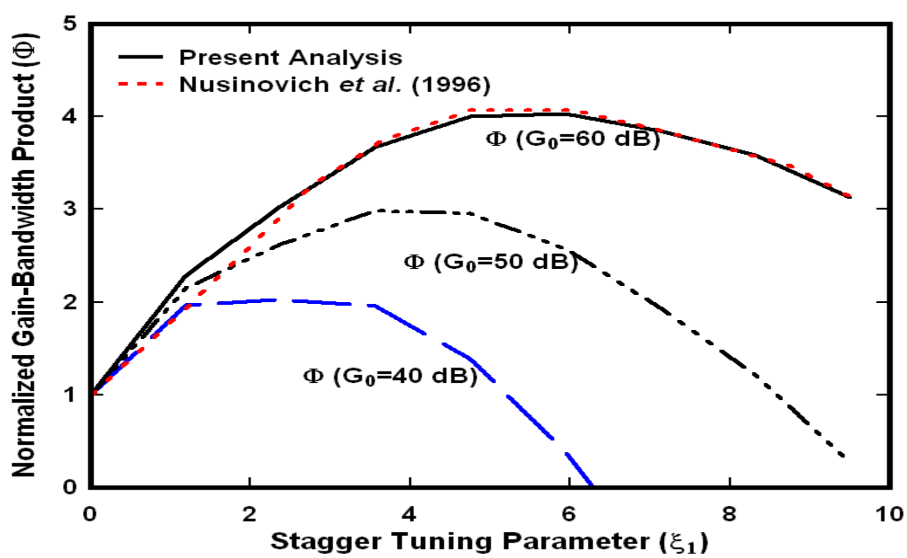


Fig. 5.5 Normalized gain-bandwidth product as a function of stagger-tuning parameter ξ_1 for $\overline{Q}$=0.2 and $\xi_2^2 = 0.2\xi_1^2$.

In the light of above facts, the normalized gain-bandwidth product of the four-cavity stagger-tuned gyroklystron amplifier is obtained in Fig. 5.5 against the stagger-tuning parameter (ξ_1) for $\overline{Q}$ = 0.2, $\xi_2^2 = 0.2\xi_1^2$ and different values of G_0,

i. e., the gain without stagger-tuning. It can be seen from Fig. 5.5, the maximum gain-bandwidth product values are obtained for smaller values of stagger-tuning parameter as compared to larger values of ξ due to less degradation in the constant gain for smaller values of ξ whereas large decrease in the constant gain occur at higher values of stagger-tuning parameter. Therefore, stagger-tuning in gyroklystron amplifier should be done to a low extent, in order to have best possible performance of the device in terms of its gain-bandwidth product.

5.4 Performance Improvement of the Gyroklystron Amplifier

As discussed above, the bandwidth of a gyroklystron amplifier is limited due to resonating nature of its cavities. It is frequently desirable to reduce the cavity quality factor by loading the cavities with suitable lossy material to increase the bandwidth of the gyroklystron amplifier to some extent ($\Delta f \approx f/Q_L$). However, this technique is unsuitable for increasing the bandwidth of the device to a larger extent as the quality factor of cavity cannot be decreased further after a certain value. It should be possible to enhance the bandwidth of the gyroklystron amplifier by using advance techniques like stagger-tuning and clustered cavity. Anyhow, the cluster cavity technique is not practical feasible for some of the reasons and a comprehensive theory for stagger-tuning gyroklystron amplifier does not exist, which would allow direct design of the gyroklystron amplifier for a specified gain bandwidth product. Optimization for a particular stagger-tuned device is obtained by trial-and error, i.e., Brute force method. Hence in the present chapter, a modest attempt has been made towards the study of the stagger-tuned gyroklystron amplifier through analytical approach. The analysis developed above is the generalized analysis for studying the effect of stagger-tuning in the four-cavity gyroklystron amplifier. Therefore, it has been used as the basis and explored further for the performance improvement of the gyroklystron amplifier designed in the previous chapter, Chapter 4.

There are two methods of tuning a practical multicavity gyroklystron — synchronous tuning, i.e., all the cavities are tuned to same frequency and the other, stagger-tuning in which each cavity is tuned to a different frequency around the center frequency. The method selection depends on the usage, whether maximum gain or bandwidth is desired. Synchronous tuning provides the highest gain and stagger-tuning provides the broadest bandwidth. In the previous chapter, Chapter 4, the results of a synchronous tuned gyroklystron amplifier were obtained to achieve the maximum possible gain. Here in order to broadband the designed gyroklystron amplifier, the stagger-tuning technique is implemented on it. A number of stagger-tuning schemes were tried in order to obtain large bandwidths and maximum possible gain-bandwidth product. The stagger-tuning in a four cavity gyroklystron amplifier can be studied by considering mainly two possible cases- first in which the eigen frequencies of the cavities modes form a non equidistant spectrum ($\xi_1 \neq \xi_2$) and in the second case the cavities mode form a equidistant spectrum ($\xi_1 = \xi_2$).

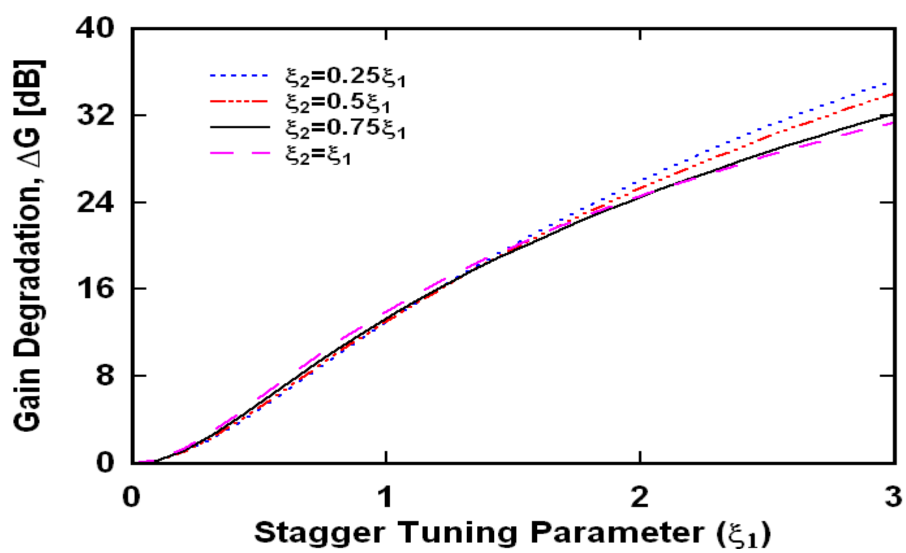


Fig. 5.6 Gain degradation as a function of stagger-tuning parameter ξ_1 for different values of ξ_2.

Fig. 5.6 shows the variation of gain degradation of the designed four cavity stagger-tuned gyroklystron as the function of the stagger-tuning parameter (ξ_1) for the different values of the stagger-tuning parameter (ξ_2). It can be easily observed from the figure that the gain degradation for the designed gyroklystron amplifier is less when both the stagger-tuning parameters are equal, i.e., the cavities modes form an equidistant spectrum ($\xi_1 = \xi_2$). Hence, in order to have a lesser amount of gain degradation one should have to use the equidistant stagger-tuning.

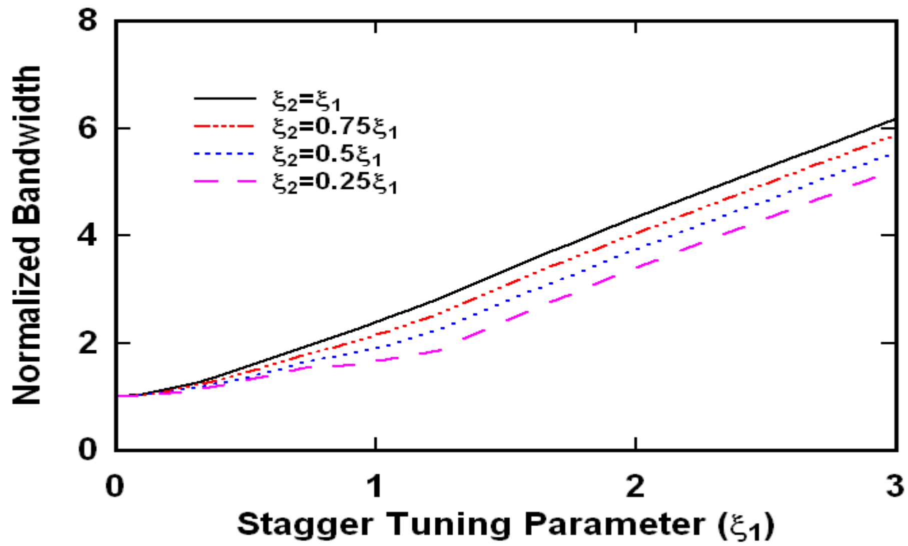


Fig. 5.7 Normalized bandwidth as a function of stagger-tuning parameter ξ_1 for different values of ξ_2.

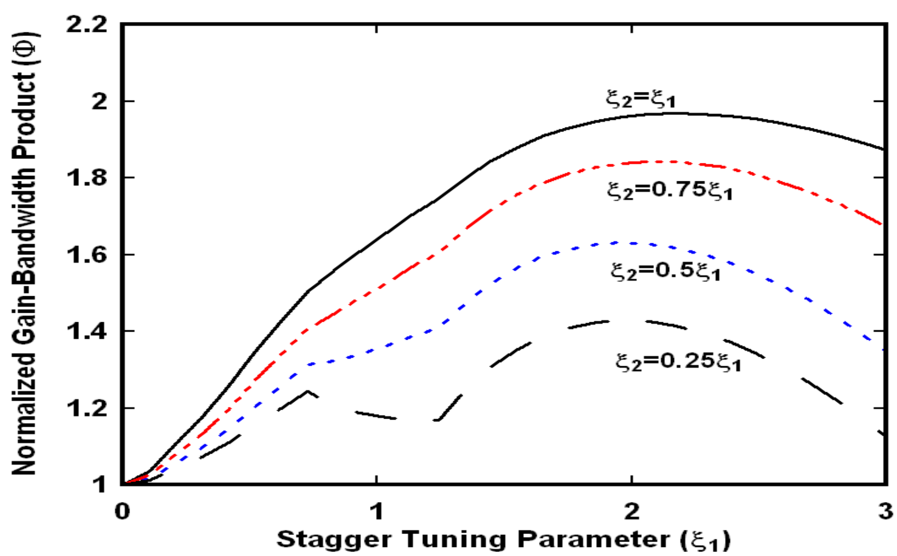


Fig. 5.8 Normalized gain-bandwidth product as a function of stagger-tuning parameter ξ_1 for different values of ξ_2 and G_0=45 dB.

In Fig. 5.7, the variation of normalized bandwidth has been plotted as the function of stagger-tuning parameter (ξ_1) for different values of stagger-tuning parameter (ξ_2). It can be seen from Fig. 5.7 that the maximum normalized bandwidth for the device is obtained for the case when eigen frequencies of the cavities modes form an equidistant spectrum ($\xi_1 = \xi_2$). In all other cases taken for study, the normalized bandwidth decreases with stagger-tuning parameter. Hence, in order to achieve maximum bandwidth from the device one should tune the cavities of gyroklystron amplifier in the equidistant spectrum mode.

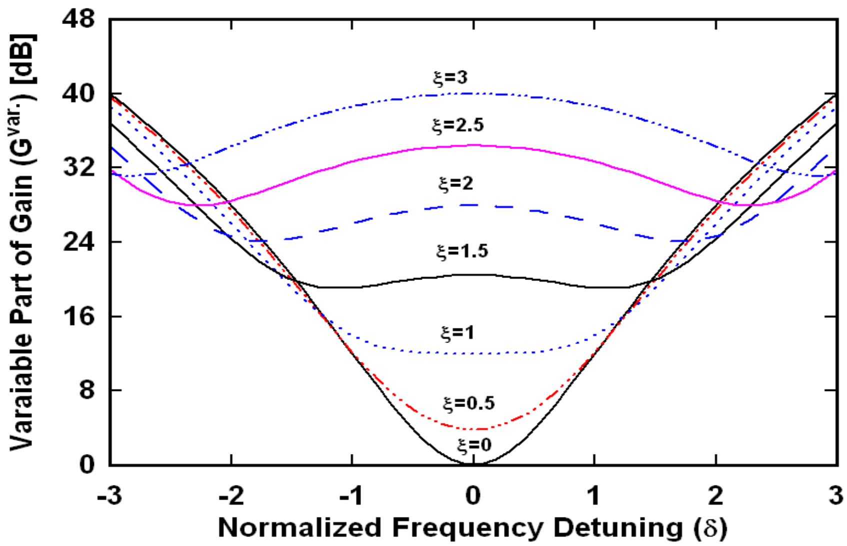


Fig. 5.9 Variable part of gain as the function normalized frequency detuning (δ) for different values of stagger-tuning parameter ($\xi_1 = \xi_2 = \xi$).

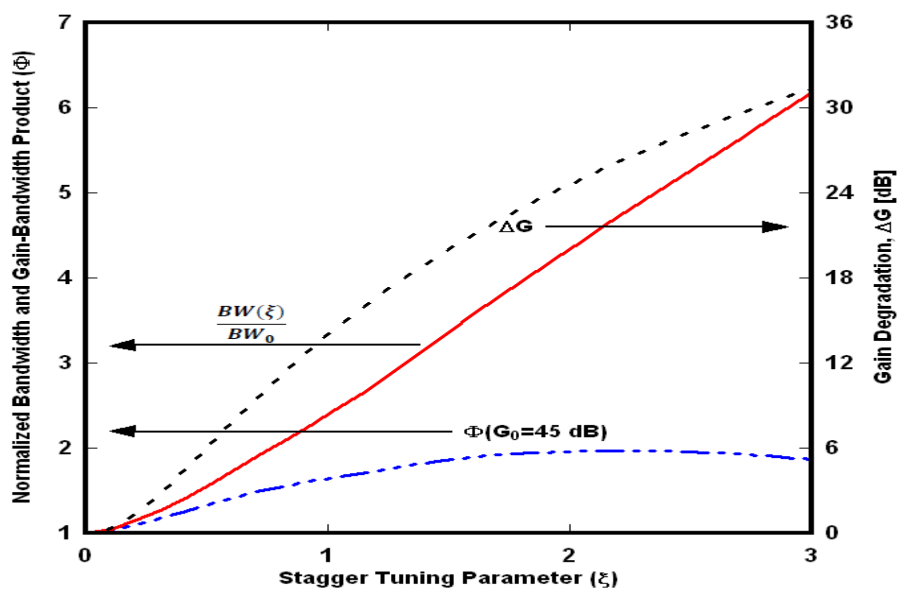


Fig. 5.10 Normalized bandwidth, gain degradation, and gain-bandwidth product as a function of stagger-tuning parameter($\xi_1 = \xi_2 = \xi$) for the designed four-cavity gyroklystron amplifier.

As explained above, that a tradeoff in gain-bandwidth product of the gyroklystron amplifier is needed for its performance evaluation rather than characterizing its performance simply by gain or bandwidth. Keeping these facts into consideration, the normalized gain-bandwidth product of the designed four-cavity stagger-tuned gyroklystron amplifier is obtained in Fig. 5.8 against the stagger-tuning parameter (ξ_1) for the different values of stagger-tuning parameter (ξ_2). It can be seen from Fig. 5.8, the maximum gain bandwidth product values are obtained for the case ($\xi_1 = \xi_2$). In other cases, the lesser values of gain-bandwidth have been observed. Hence, from Figs. 5.6, 5.7 and 5.8, one can easily conclude that in order to achieve maximum gain-bandwidth product with larger bandwidth and lesser gain degradation, the device has to be stagger-tuned in such a way that the frequencies of cavities modes form an equidistant spectrum ($\xi_1 = \xi_2$).

The dependencies of variable part of gain ($G^{var.}$) upon frequency detuning (δ) given by equation (5.16) for different values of stagger-tuning parameter ($\xi_1 = \xi_2 = \xi$), are shown in Fig. 5.9. One may see that the Fig. 5.9 is symmetric with respect to frequency detuning of the RF cavities (δ). It means that the same amount of gain degradation will occur at both side of the curve for a particular value of RF cavity detuning (δ) either delta is positive or negative. Hence, the bandwidth of the device will not be affected by the sign of the stagger-tuning parameter (ξ). It remains same for a specific value of RF cavity detuning parameter (δ), which is either positive or negative.

The combined plots of the normalized bandwidth, gain degradation and gain-bandwidth product as functions of the stagger-tuning parameter ($\xi_1 = \xi_2 = \xi$) for the designed four-cavity gyroklystron amplifier are shown in Fig. 5.10. The results obtained for four-cavity stagger-tuned gyroklystron amplifier shows nearly two times more gain-bandwidth product enhancement around $\xi = 2$ as compared to the four-cavity gyroklystron without stagger-tuning ($\xi = 0$). The results obtained here will be further verified in the next section by carrying out the PIC simulation of the designed four-cavity gyroklystron amplifier for different values of stagger-tuning parameter.

5.5 Validation through PIC Simulation

In order to validate the analytical results obtained in this chapter, the effect of stagger-tuning on the designed four-cavity gyroklystron amplifier has been studied in detail using the 3-D PIC simulation tool MAGIC. Table 5.1 show the tuning eigenfrequencies of each individual cavity corresponding to different values of stagger-tuning parameter for the equidistant stagger-tuning mode spectrum. In the simulation, the desired tuning of the frequencies in each cavity has been accomplished by varying their radius.

Table 5.1 Frequency variation in each cavity corresponding to different stagger-tuning parameter (ξ).

ξ	f_1 (GHz)	f_2 (GHz)	f_3 (GHz)	f_4 (GHz)
0	35.00	35.00	35.00	35.00
0.25	34.955	34.97	34.985	35.00
0.5	34.91	34.94	34.97	35.00
0.75	34.865	34.91	34.955	35.00
1	34.82	34.88	34.94	35.00
1.25	34.775	34.85	34.925	35.00
1.5	34.73	34.82	34.91	35.00

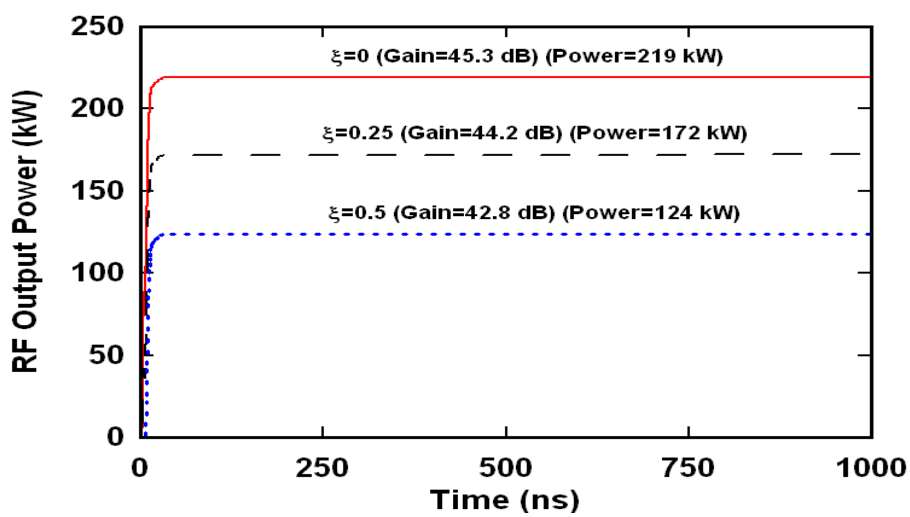


Fig. 5.11 Temporal growth of RF output power for different values of stagger-tuning parameter ξ.

Fig. 5.11 show temporal profiles of observed RF output power corresponding to 6.5W RF input power measured at the output port of the output RF cavity for different values of stagger-tuning parameters. It is quite obvious and easily pointed out from the figure that with the increasing value of stagger-tuning parameter the RF output power alongwith it the corresponding gain of the device decreases. As, it can be easily seen from the figure, that the radiated RF output power of 21 kW with 45.3dB gain is obtained without stagger-tuning (ξ = 0) whereas RF output power around 172 kW with 44.2 dB gain, and 124 kW with 42.8 dB gain were obtained for stagger-tuning parameter ξ = 0.25 and ξ = 0.5, respectively.

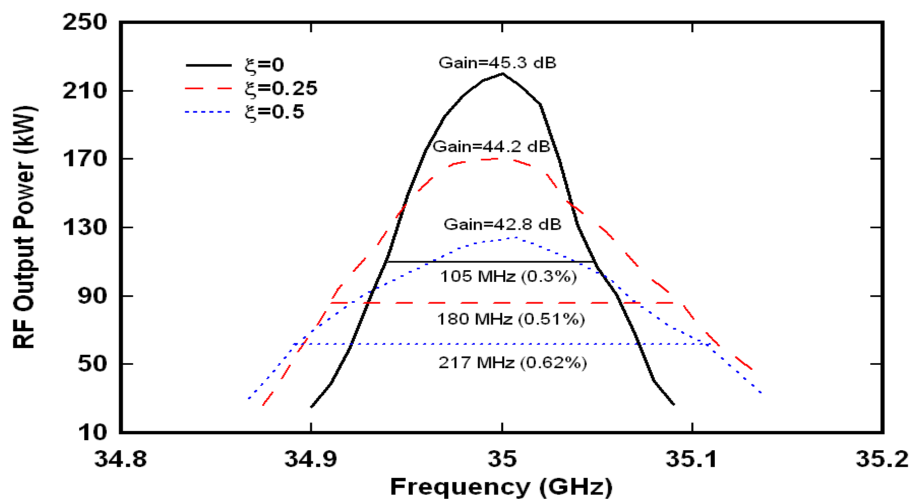


Fig. 5.12 RF output power as a function of frequency for different values of stagger-tuning parameter ξ.

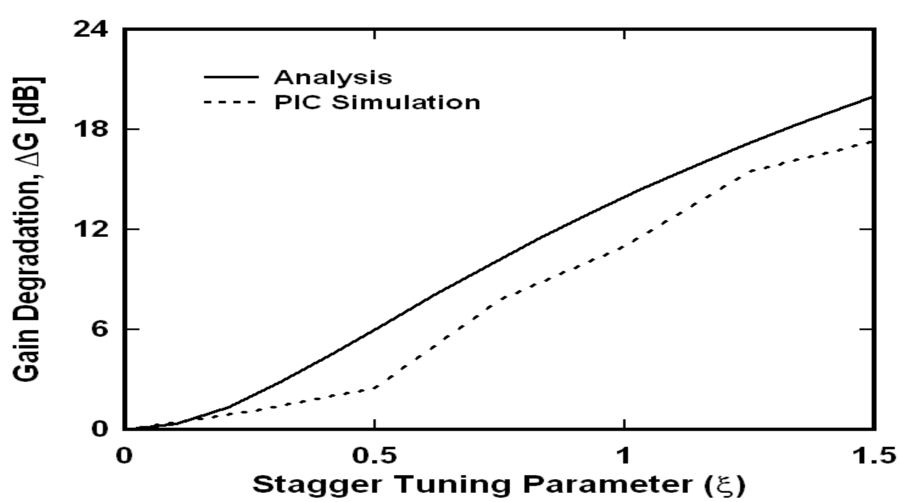


Fig. 5.13 Gain degradation as a function of stagger-tuning parameter ξ.

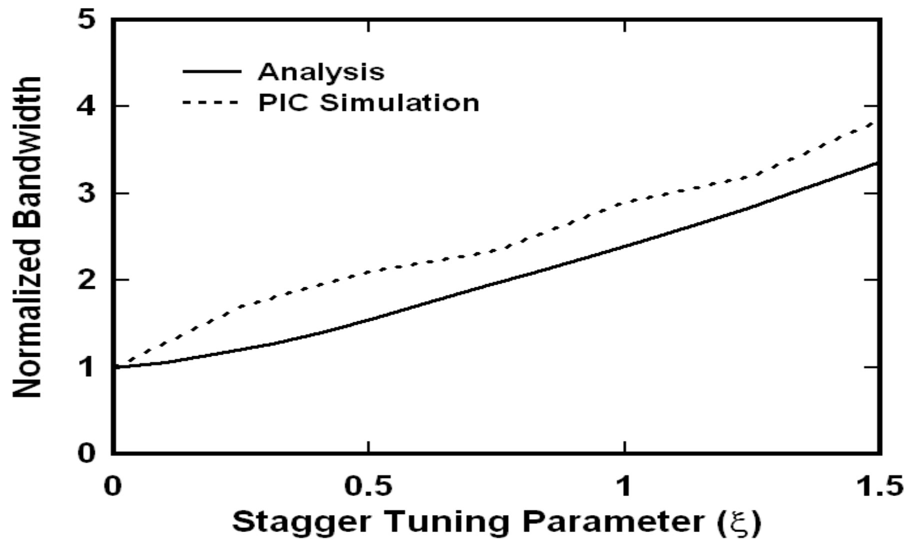


Fig. 5.14 Normalized bandwidth as a function of stagger-tuning parameter ξ.

In Fig. 5.12, the variation of output power as a function of frequency has been shown for different values of stagger-tuning parameter. One may see from Fig. 5.12 that the bandwidth of the device is increasing with value of stagger-tuning parameter. In Fig. 5.12, the maximum output power is obtained ~ 219 kW at center frequency 35 GHz for without stagger-tuning (ξ = 0) with bandwidth 0.3% (105 MHz) whereas RF output power around 172kW with bandwidth 0.51% (180 MHz), and 124kW with bandwidth 0.61% (217 MHz) were obtained for stagger-tuning parameter ξ = 0.25 and ξ = 0.5, respectively. It means that there is about two times enhancement in the bandwidth of the device with loss of 2.5dB gain as the value of stagger-tuning parameter increases from 0 to 0.5. Based on these results, one can conclude that by selecting a nominal amount of stagger-tuning, the bandwidth of the gyroklystron amplifier can be enhanced with some loss of its gain.

The gain degradation and normalized bandwidth plots for the designed four-cavity gyroklystron amplifier obtained through analysis and PIC simulation are compared in Figs. 5.13, and 5.14, respectively, for the validation purpose. It can be seen from both the figures that the results obtained from both the techniques are within 10% agreement.

5.6 Conclusion

In the present chapter, Chapter 5, the gyroklystron amplifier is explored further for its performance improvement in terms of the device bandwidth. One of the major limitations of the gyroklystron amplifier is its limited bandwidth operation, since it utilizes a series of resonant cavities for its beam-wave interaction structure. Thus, in the present chapter, effort has been made towards enhancement of bandwidth of the gyroklystron amplifier using stagger-tuning technique. The concept of stagger-tuning is frequently used in conventional klystrons for their bandwidth enhancement. In this method, the eigenfrequencies of different RF interaction cavities of a klystron amplifier are slightly detuned, due to which the enhancement in the bandwidth of the device occurs, but at the cost of its gain. The same concept is utilized in the present chapter for the bandwidth enhancement of the gyroklystron amplifier as gyroklystron is simply a combination of gyrotron and klystron. In the present work, we have studied a tradeoff in gain and bandwidth alongwith gain-bandwidth product for the stagger-tuned gyroklystrons. As, gain-bandwidth product is an important factor and treated as a figure of merit for amplifiers in many applications. First, the generalized formalism for stagger-tuned gyroklystron amplifiers has been developed. The developed formalism has been numerically appreciated by studying the effect of stagger-tuning on the designed gyroklystron amplifier. The analytical results obtained here have been validated with the help of the PIC simulation results, and a fair agreement between the results (<10%) obtained from both the approaches have been found.