Chapter 6

Conclusion and Future Scope

6.1 Conclusions

This dissertation focuses on the ultra-broadband graphene-based devices having tunable, compact and ultrathin characteristics altogether operating within the THz gap (0.1-10 THz). In conclusion one reader can understand the futuristic electromagnetic applications of the patterned graphene in metasurfaces offering show distinctive properties. Conventional metasurfaces incorporate metallic nanostructures to obtain required amplitude, phase, or polarization orientations in reflective mode as well as in transmission mode. Metallic nanostructures support intense surface plasmon resonances at the optical spectral region. The same plasmonic response reduces to the weaker one while approaching the mid-infrared (MIR) or THz region as the interactions between the electrons and the EM wave become less strong. Graphene has been surfaced as the most promising and a potential alternative contender for plasmonics in the THz and MIR spectral regions. Additionally, graphene exhibits tunable Fermi energy level which makes graphene a suitable material for the tunable optical prototypes. Graphene can be considered as a single slice cut out from a graphite block made of a mono layer of carbon atoms distributed in the form of a hexagonal lattice. Therefore, graphene-based devices can achieve broadband responses by maintaining compact and ultrathin characteristics. In this thesis, the fundamentals of graphene have been discussed first to understand the physics, mathematics and chemistry for using it as a metasurface. The basic properties of graphene have been introduced. The existing limited EM applications of graphene metasurfaces are reviewed.

Chapter 2 describes two types of broadband absorbers offering distinctive achievements. Broadband absorption of the EM wave is possible because graphene can allocate significantly high plasmonic resonances. The first device has achieved fractional 90% absorption bandwidth. The second prototype reports a higher value of fractional absorption bandwidth of 140.86%. The broadband absorption responses of the above-said two designs have proved the surface plasmon resonances (SPR) and localized surface plasmon resonances (LSPRs) of the patterned graphene metasurfaces under the exposure of the incident EM wave.

Chapter 3 talks about graphene metasurface-based rasorber having EM wave absorption property as well as transmission property. The configuration of such rasorber device includes two sub-wavelength periodic structures on two opposite sides of the substrate. The electromagnetic property of the top graphene metasurface helps to absorb the EM wave in the lower THz band while the bottom slotted metasurface works as a reflector at some frequencies and a filter at other frequencies. Further, all these electromagnetic properties have been validated using an inhouse specific circuital approach. Values of all circuit components have been deduced. The EM simulated outputs and the circuit model results are in excellent resemblance.

Chapter 4 includes the design and development of a graphene-based reflective-type slotted metasurface that converts the linearly polarized EM wave into its circularly polarized form. Two elliptical slots arranged perpendicularly have been embedded into one unit cell of the proposed metasurface to manipulate the magnitude and phase of the EM wave. Therefore, under the exposure of the linearly-polarized wave, it produces the circularly polarized wave. Due to its continuous nature, the as-proposed metasurface can be easily electrically biased by applying a variable dc voltage between the top and bottom surfaces. This device reports a 3 dB axial ratio bandwidth of 2.25 THz within the lower THz region. The tunability property of this device has been verified by producing the polarization ellipses at different ranges of frequencies by an externally applied static electric field. Furthermore, the EM simulated results have been compared with the inhouse circuit model approach and they agree well.

This chapter also provides a design illustration of a transmittive-type triple-band linear to circular polarization converter (TTLCPC) within the lower mid-infrared (MIR) region covering the THz gap. The device has a periodic graphene pattern on top surface and the backside of it is covered with a periodically-slotted gold layer. The circular nature of the transmitted wave has been verified with the calculation of the Stokes' parameters. The design configuration of the TTLCPC has been realized in terms of a circuit schematic to have a clear idea about the device. Further, the circular polarization nature of the transmitted wave at three frequency bands has been verified using an inhouse code by forming polarization ellipses.

Chapter 5 describes the design of a dual-functional metadevice which can be operated for two different applications simultaneously without making any structural deformations. Under the exposure of the EM wave this device can manipulate the wave for absorption and cross-polarization conversion under two distinct electric fields. The multi-layered design consists of graphene-metal hybrid combinations to exhibit dual functionality. The device offers more than 70% absorptivity over a bandwidth of 3.40 THz (between 4.25 THz and 7.65 THz) with a 90% absorptivity peak at 6.84 THz under the static electric field of $\xi = 8.52$ V/nm. The device can also produce a cross-polarization conversion ratio (PCR) of more than 90% over a bandwidth of 3.87 THz (between 2.22 THz - 6.09 THz) with near-unity PCR peaks at 2.38 THz, 3.80 THz and 5.82 THz, respectively at $\xi = 0.44$ V/nm. The device is very promising for futuristic applications as it performs dual functionality from a single physical configuration without integrating of lumped elements. The device finds potential applications for THz detection, THz communication, THz imaging, THz sensing, wearable and portable electronic devices, 5G/6G communications and beyond.

Chapter 6 includes the conclusion and future scope of the thesis.

Potential future plans for the designed graphene metasurface enabled devices:

1. The physical realization and experimental verifications of the proposed devices described in Chapter 2 to Chapter 6 will be an attractive future plan in this context. The graphene patterns can be deposited on SiO_2 substrate; and some of the experimental set-up is available in different labs in foreign countries. Therefore, we can go forward in this direction to explore further. Moreover, in some designs, we have shown how the devices can be tuned by applying a gate voltage induced by the external electric field.
2. The formation of localized surface plasmons is the primary and foremost requirement of all graphene-based structures for efficient THz and infrared frequencies. Nevertheless, many more probable applications can be allocated if their plasmon working frequencies can be expanded to near-infrared (NIR) or even visible spectral regions. This may be done by incorporating high doping in graphene, or forming graphene-metal hybrid structures. Some of design description shows the way on how one can achieve tunability in the spectral axis under the application of the external static electric filed.
3. Graphene metasurfaces are advantageous in producing broadband and lightweight absorbers and polarizers. The ongoing research focuses on hybrid multilayered configurations in extending their frequencies of operation to cover the whole THz range. This is a top priority for future research. We proposed single and double-layered graphene metasurfaces for broadband absorber applications in Chapter 2.
4. The formation of localized surface plasmons (LSPs) in graphene is a unique feature which can improve the local electric field further resulting into the increment of the EM wave absorption or nonlinear response. We have proposed graphene metasurface-based devices attaining this feature. Still, many more experimental works should be conducted to explore new possibilities. For commercial purpose, the cost and complexity of the experimental set up should be reduced.

5. In general, loss affects the performance of the devices. We are planning for some EM applications to use the unavoidable loss of graphene.

6.2 Suggestions for future research

Metasurface-enabled devices operating in the THz spectrum are gathering their suitability in multiple applications, such as thermal imaging, solar harvesting, spatial light modulators, perfect absorbers, and polarization converters. It is hard to engage a naturally occurring substance due to the electric and magnetic resonances breakpoint at those frequencies. Additionally, the physical implementation of some specific applications at microwave frequency range in terms of active or passive components in the design is not executable in near-infrared (NIR) or visible regions. Metallic metasurface-based structures are able to tackle the desirable properties in the near-infrared or visible regions frequencies. But, graphene metasurface is more suitable for THz gap applications. The following paths are suggested for the future research:

1. The graphene metasurface can be studied for a short-distance communication.
2. Bi-directional THz devices can be explored further.
3. Coding metasurfaces can be implemented using graphene metasurface to design direction-independent devices.