Terahertz guided mode propagation in a planar plasmonic waveguide and slow light properties

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Abstract: We examine terahertz guided mode properties of a plasmonic waveguide comprising periodic corrugations along the direction of propagation as well as within the structures. We also analyse the slow light properties of the guided modes.

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Introduction:

Recently, THz region in electromagnetic spectrum has attracted wide attention because of their various applications such as communication, sensing, nonlinear phenomenon etc. [1, 2]. In last one decade, much emphasis has been given to the development of efficient THz waveguides as they are essential components to any passive or active system [3, 4]. For instance, Kumar et al have experimentally investigated plasmonic terahertz waveguide by patterning heavily doped silicon substrate. [4]. Such plasmonic waveguide geometries support highly confined guided modes that exhibit slow light properties or in other words lower group velocity of the modes. The slow light systems have significance in photonics and are used in making devices such as optical buffers, storage systems etc. [5-7]. In this context, Baba et al have experimentally investigated a slow-light waveguide based on photonic crystal for buffering [8]. More recently, Zhang et al numerically reported slow-light phenomena in periodic plasmonic waveguides [9]. These investigations have been mostly carried out in the optical or near infrared domain. In terahertz domain, very few investigations have taken place in this area. Gan et. al have reported slow light system at terahertz frequencies based upon graded grating structures [10]. But still one can improve waveguide devices based on slow-light phenomena in THz regime as it has a lot of applications. In order to make practical slow light devices at terahertz frequencies, the plasmonic waveguides are required to be extensively investigated for the optimum geometry resulting to the lower group velocity and their properties.

In this paper, we analyse terahertz plasmonic waveguides composed of different types of corrugations along the waveguide as well as within the structures. We first numerically calculate the dispersion relations of the fundamental modes supported under different corrugations. Next, we examine the time-domain and frequency domain waveguide transmission for the proposed waveguide geometries. Further, we examine the group velocities of the fundamental modes and investigate corresponding slow-down factor in corrugated waveguide geometries. The results are summed up in conclusions section.

Waveguide Geometry

In order to examine guided mode properties and their slow light behaviour in plasmonic waveguide, we have studied three different types of corrugations. These corrugations include long rectangular, pyramidal and V-shape dimples. It may be noted that if one increases the number of steps to infinity in pyramidal shaped corrugations then the structure will behave as a V-shape structure. The schematic of the proposed THz waveguide with pyramidal corrugations is shown in Figure 1. Figure 1(a) shows a 3 dimensional view of the waveguide comprising periodic corrugations of pyramidal shape, whereas (b) depicts a side view of that waveguide. Throughout the study, the length (l) = 200μm, width (w) = 1500μm, depth (h) = 350μm, periodicity (p) = 250μm of different corrugations are kept constant.

Results and discussion

In order to examine THz mode propagation of the waveguides with three different corrugated patterns, we examined dispersion relations of the fundamental mode using a Finite Element Eigen mode solver, with the periodic boundary condition along propagation direction and absorbing layers along the transverse direction. We have assumed perfect
electrical conducting (PEC) boundary condition for metal substrate owing to its high conductivity at terahertz frequencies. The results of the dispersion relations for different dimples patterns are shown in Figure 2 (a). One may note that the straight line exhibits light line. The other coloured traces correspond to dispersion relations of fundamental mode for different dimples which are mentioned in the figure. One can notice that, for a particular corrugation, initially frequency monotonically increases with the wavenumber and then saturates. For rectangular shape dimples we get a saturation frequency at 0.18 THz. This value ideally corresponds to zero group velocity and therefore it is also termed as cut-off frequency of the fundamental mode. The plasmonic response of the waveguide is only observed below the cut-off frequency. As we change the shape of dimples, the dispersion curves shift towards the light line and saturates to higher values. For pyramidal and V-shape dimples the cut-off frequencies turn out to be 0.24 THz and 0.26 THz respectively. In our study, each type of waveguide pattern has a certain cut-off frequency i.e. they have zero group velocity at a certain frequency, which means that significant slow-light effect can be a useful outcome of our proposed waveguides. In this context, we examine the slow-down factor \( c/v_g \) of the fundamental terahertz mode propagation in different types of waveguide geometries. Here ‘c’ and ‘\( v_g \)’ represent velocity of light in free space and group velocity of fundamental mode respectively. The slow-down factors for different geometries have been shown in Figure 2(b). Hence, one can notice that the slow-down factors can be tuned at different frequencies by changing the shape of the corrugations.

Further, we examine the terahertz waveguide transmission for our proposed waveguide structures. We excite our planar terahertz waveguides with a discrete source of single cycle terahertz waveform from one end of the waveguide. The terahertz signal propagates along the dimpled patterns and is detected at the other end of the waveguide. This time domain signal is finally converted into the frequency domain spectra using fast Fourier transform (FFT) approach.
For our simulations, we used finite element time domain solver of the CST Microwave Studio simulation software. First, we examine the 3 cm long planar waveguide with rectangular shape dimples, then similarly for pyramidal and V-shape dimples. The results in the form of frequency domain spectra are shown in figure 3(a). One may note that the anti-resonant frequencies obtained from frequency domain spectra match with the saturation frequencies for respective dimple patterns. In order to understand the mode profiles, we also examine the electric field profiles of the terahertz fundamental modes supported by these waveguide geometries. Figure 3 (b) and (c) show the field profile of the fundamental plasmonic mode at frequencies 0.18 THz and 0.26 THz supported by rectangular and V-shape dimples, respectively. The fields are tightly confined within the cavities at their respective resonant frequencies indicating a highly confined guided mode propagation.

**Conclusion**

In conclusion, we have examined the terahertz guided mode propagation in a plasmonic waveguide comprising sub-wavelength scale corrugated structures of different shapes. In all the cases, dispersion relations of the fundamental modes are drifted away from the light line, indicating a plasmonic response of the waveguide. We observed that rectangular structures exhibit lower cut-off frequency resulting in the lower group velocity of the fundamental mode. At 0.18 THz, we observed slowdown factor $(c/v_g) \sim 0.4, 0.02$ and 0.018 for rectangular, pyramidal and V-shape dimples, respectively. So, our study shows that rectangular dimples are more efficient for slowing down the light. The slow-light properties of the modes could be significant in making terahertz buffers and storage device.

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**References**


**Figure 3:** (a) Frequency domain waveguide transmission spectra for the plasmonic terahertz waveguides comprising corrugated patterns of three different shapes. (b) and (c) Show the field profiles of the fundamental plasmonic mode for rectangular and V-shape dimples at 0.18 THz and 0.26 THz respectively.