Terahertz surface plasmon polaritons propagation in slanted pillar geometries

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Abstract: In this paper, we present detailed numerical study of periodically corrugated surfaces to establish the directional dependence of terahertz (THz) surface plasmon polaritons propagation. A metal surface approximated as perfectly electrical conductor at terahertz frequencies, is periodically patterned with slanted sub-wavelength scale pillars forming a plasmonic waveguide. The slanted pillar geometries are found to support highly confined terahertz modes at specific frequencies which can be tailored with the slanted pillar parameters and their angle of tilt with respect to the normal. The terahertz mode propagation with different angles through which pillars are tilted w.r.t. the normal is examined in detail. From these results we observed that the slanted geometries are more efficient in guiding terahertz in a particular direction.

Introduction:
In recent years, there has been significant interest in developing devices and networks for high speed communication. THz radiations covering a frequency range of 0.3 to 3THz has been examined in last more than a decade for various applications including high speed communication [1-4]. THz waves can promise data transfer at much higher speed because of their ability to transfer data signals at tera bits per second. However to realize devices operating at terahertz one need to develop efficient waveguides exhibiting low loss and high directional confinement to transfer signals [5-7]. In this direction, a lot of research has been reported in last more than a decade both experimentally and theoretically [8-12]. Williams et al. first time experimentally reported the highly confined surface plasmon polaritons propagation by structuring a dielectric and depositing a thick copper layer on it [13]. Around the same time, Zhu et al. designed and fabricated one dimensional array of apertures in a thin stainless steel foil and thereby forming a planar plasmonic waveguide and experimentally demonstrated straight and passive guided wave devices [14]. In an attempt to reduce propagation loss Kumar et al. experimentally examined the ability to guide THz radiation using 1D arrays of periodically spaced rectangular blind holes in metal films [15]. The blind hole pattern led to the propagation of THz surface plasmon only on one side of the waveguide thereby reducing loss. The waveguiding approaches in guiding terahertz on a planar surface as discussed above have been inspired by the seminal work by sir Pendry and co-workers in 2004 [16].

In last decade, there have been several theoretical studies reported as well on THz waveguides. In this respect, Wood et al. investigated dispersion properties of surface plasmon polaritons in slanted dimpled surface patterns and examined their field confinement [17]. Rusina et al. has developed fundamental understanding in designing the optimum and efficient metal /dielectric nanowaveguides
suitable for the THz nanofocusing [18]. They reported nanoconcentration of THz radiation by considering a parallel plate waveguide that consists of a dielectric slab sand-witched between two thick metal plates. Making further advancement in the field of THz plasmonic based waveguides, Kumar et al. showed propagation of THz beam on a heavily doped silicon surface patterned with pillars [6]. They observed that patterned silicon surface acts as an effective medium for highly confined terahertz surface mode propagation. Although these developments on terahertz waveguides have been able to overcome several hurdles in the field of THz science and but active and passive components in this narrow range of frequency are still lacking. One of the challenge has been to selectively guide a terahertz modes in a particular direction than the other in an efficient way.

The guiding of terahertz in a particular direction under the low divergence can lead to variety of applications such as long distance sensing, identification [19] and high speed transmission of information. In THz planar plasmonic waveguides, we discover than one can bend or tilt the corrugated structure to transfer terahertz signal more efficiently in a particular direction than the other. We have addressed this ability by designing slanted pattern on a thin metal sheet approximated as perfectly electrical conductor at terahertz frequencies.

In this paper, we design terahertz planar plasmonic waveguides by periodically corrugating a thin metal surface with slanted pillars. The sub-wavelength scale pillars tilted as different angles ensure the plasmonic response in our numerical analysis. We performed both time domain and frequency domain numerical simulations to precisely analyse the mode propagation in plasmonic waveguides comprising pillars at different angles. While placing the sources at the centre of the waveguide and detectors at both the ends, we examined terahertz waveguide transmission with different tilting angles of the pillars. Finally we summarize the results in the conclusion section.

Waveguide geometry and Dispersion properties:
We designed and numerically examined several waveguide geometries with varying angle of slanted pillars. The schematic of the designed planar THz waveguide is shown in Figure 1. Figure 1(a) shows a 3 dimensional view of the waveguide, whereas (b) depicts a side view of the waveguide. Throughout our study, length (l), width (w), height (h), and periodicity (p) of the tilted pillars are kept constant. These parameters are: length (l) = 100µm, width (w) = 500µm, height (h) = 100µm, periodicity (p) = 400µm. In order to examine the effect of angles through which the pillars are tilted w.r.t. normal on the terahertz surface mode propagation, we considered pillars with different tilt angles of 5°, 10°, 20°, 40° and 60°.

![Figure 1](image1.png)

(a) (b)

Figure 1: Schematic of the planar THz waveguide. (a) 3-Dimensional view of the waveguide comprising one dimensional array of pillars tilted with respect to the surface. The other constant parameters labelled as ‘l’, ‘w’, ‘h’ and ‘p’ are length, width, height, and periodicity respectively. (b) Depicts the side view of pillar patterned waveguide with pillars making angle θ with the normal.

In order to examine THz mode propagation in slanted pillar geometries, we examined dispersion relations of the pillar waveguides using a Finite Element Eigen mode solver, with the periodic boundary condition along propagation direction and absorbing layers along the transverse direction. The dispersion relations are calculated for two waveguides with pillars tilted at 10° and 60°. The dispersion relation was calculated by numerically modelling one unit cell of the periodic structure. Perfect electrical conducting (PEC) boundary condition was assumed for the pillar waveguide owing to the high conductivity of metal at terahertz frequencies. Figure 2(a) shows dispersion relations of slanted
waveguide pattern. The blue and red curves correspond to surface electromagnetic modes supported by the pillars tilted at angle $10^\circ$ and $60^\circ$ respectively. Here, initially we get monotonic increment of frequency and corresponding phase i.e. wavenumber. Up to a certain phase, there is a constant group velocity since the dispersion relation exhibit linear relationship between the frequency and wavenumber and after that we get a saturation in the dispersion i.e. zero group velocity at frequency $0.31\text{THz}$ for tilt angle $10^\circ$ and at frequency $0.22\text{THz}$ for tilt angle $60^\circ$. But just before the saturation, there will be a constant phase velocity. In these slanted waveguide, we observed that dispersion relation shifting away from the light line when these pillars are more tilted with respect to surface.

![Figure 2](image)

**Figure 2:** (a) Numerically calculated dispersion properties for the pillar patterned waveguides with pillar tilted at angles $10^\circ$ and $60^\circ$ with respect to normal.

**Result and discussion:**

We use modified technique of terahertz time domain spectroscopy to examine the designed slanted pillar patterns. We numerically obtain the time domain signal of the terahertz waveform at the other end of the waveguide using a waveguide port and convert it to frequency domain signal using Fast Fourier Transform. The waveguide transmission spectra are obtained using finite element time domain method. First, we examine the 3 cm long planar waveguide with pillars tilted at $5^\circ$. The results in the form of frequency domain spectra are shown in Figure 3. The inset shows the corresponding time domain signal. One may notice a resonant behaviour in the spectra with anti-resonant frequency at $0.31 \text{THz}$ in the present case. In our numerical analysis, we observed a very little change in the anti-resonant frequency with a change in the angle of pillars because of the slight change in the height of the pillars when they are tilted. However, one may observe a significant change in the resonant frequency when height of the pillars is changed.

Next, we examine the terahertz mode propagation of the terahertz modes in the forward and backward directions of the pillar patterned waveguides and compare the results. We place the terahertz source in the middle of the 4 cm long waveguide and examine terahertz modes at 2 cm distance from the source in both the directions. The pillars of the waveguide are tilted in one direction. The frequency domain spectra indicates a difference in output waveguide amplitude calculated at both the ends. The results are shown in Figure 3(b). The blue and red traces represent signal in the forward and backward directions respectively for the pillars tilted at $60^\circ$. We observe a higher waveguide transmission in the forward direction i.e. the direction in which pillars are tilted. We get an output amplitude of $\sim 95\%$ in the forward direction compared with the $54\%$ signal amplitude in the backward direction for the wave propagation of same distance in both directions. Therefore the proposed waveguides, allow us to propagate the signal more efficiently in one direction by changing the angle through which pillars are tilted. One may also control the THz waveguide transmission depending of the angle.
Figure 3: (a) Numerically simulated waveguide transmission spectrum on a PEC substrate patterned with slanted pillars at an angle 50° w.r.t the surface. The other parameters are: length ‘l’ = 100μm, width ‘w’ = 500μm, height ‘h’ = 100μm and periodicity ‘p’ = 400μm. The inset shows the corresponding time-domain spectrum. (b) Frequency domain spectra of the pillar patterned waveguides with pillar angle 60° w.r.t. normal in forward and backward directions. The detectors are placed at a distance of 2 cm from the centre from both the ends.

Figure 4: (a) Field profiles in the x-y plane of the waveguide at ON-resonance (0.31THz) and OFF-resonance (0.5THz) frequency.

In Figure 4, we examine the field profile of the terahertz mode supported by a particular waveguide with slanted pillars for the parameters: length (l) = 100μm, width (w) = 500μm, height (h) = 100μm, periodicity (p) = 400μm and tilt angle of 60° with respect to normal. The field profiles are examined at the ON-resonance (0.31 THz) and OFF-resonant frequencies (0.5THz). One may note that at resonant frequency, the field is highly confined to the pillars geometries, however it is leaking away from the surface at other frequencies not at resonance. It is to be mentioned that in our numerical study, we have assumed tetrahedral shaped grids of size ~λ/10 indicating sub wavelength regime.

We next consider one essential property of the periodic slanted pillars waveguide pattern, which is confinement and that is relevant for waveguide application. Firstly, we analyse confinement along vertical direction. We have numerically measured the vertical confinement by finite-difference time-domain simulation for the slanted pillars at angle 40° with respect to normal, by translating the detectors away from the surface. Figure 5(a) plots the measured peak spectral amplitude as a function of distance above the surface, along with an exponential fit which brings out a 1/e length of 0.25mm approximately. After that, we considered the confinement of the terahertz modes in both the transverse directions by placing detectors at different position in order to have a comprehensive understanding of the THz mode.
propagation. The horizontal confinement of the resonant mode was calculated also by finite-difference
time-domain simulation. Figure 5(b) plots the calculated field amplitude as a function of the transverse
coordinate z also for slanted pillars pattern at angle 40° with respect to normal, which shows a full-
width at half-maximum (FWHM) of approximately 500µm from the Gaussian fit of the results. The
information on the waveguide transmission properties could be useful in fabrication and further
demonstration of such waveguide experimentally. It may be noted that although our study on slanted
geometries is based on numerical simulations, but one can fabricate such waveguides on
semiconductors. One may explore deep reactive ion etching for fabrication of slanted structures with
suitable arrangement of the substrate in tilted configuration.

![Figure 5](image)

**Figure 5:** (a) THz waveguide transmission of the THz signal probed at different positions above the
surface. The data is exponentially fitted to obtain 1/e propagation length. (b) A plot of THz field
measurements in lateral direction to estimate the confinement of propagating wave in the lateral
direction.

**Conclusion:**
Briefly, we have examined in details the planar plasmonic terahertz waveguides comprising sub-
wavelength scale pillars tilted at different angles. We have numerically calculated the dispersion
relations of the fundamental Eigen modes supported by slanted pillar waveguides. It is observed that a
change in the angle of tilt results in a change of dispersion properties. We confirmed the existence of
various surface modes in dispersion relations independently through the time domain and frequency
domain solver. A change in the angle of tilt changes the cut-off frequency of the terahertz supported by
the pillar waveguide. Further, we analyse the terahertz transmission amplitude at two opposite ends of
the waveguide by placing source at the centre with pillars tilted in a particular directions. We found that
transmission is more than 40% in the direction of tilted pillars. This clearly indicated that one can guide
terahertz in a particular direction more efficiently with suitable designing parameters. We have also
calculated the mode confinement above the surface (1/e propagation length ~ 0.25mm) and on the
surface along transverse directions (FWHM ~ 0.5mm). The field profiles of the modes indicates a strong
confinement at the resonant frequencies. The terahertz waveguides discussed here could play a crucial
role in designing active devices and networks at terahertz frequencies.

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