Planar plasmonic terahertz waveguides based on periodically corrugated metal films

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Abstract. We demonstrate that a one-dimensional periodically corrugated metal film can be used to create planar terahertz (THz) waveguides. The periodic corrugation is in the form of rectangular blind holes (i.e. holes that do not completely perforate the metal film) that are fabricated using a multilayer construction. The approach allows for the creation of structures in which the hole depth can be more than four times the hole width. This is necessary to achieve tightly confined THz guided-wave modes. We find that the modes can be modeled using an effective cavity resonance model and that the mode properties depend sensitively on the depth of corrugation. We use numerical simulations to validate the experimental results. We also highlight the differences between simulations that incorporate idealized input parameters and our experimental measurements. Using these data, we fabricate and characterize a Y-splitter to demonstrate the utility of this approach.

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1. Introduction

In recent years, there has been great interest in examining materials that are artificially structured on a subwavelength scale. These materials, often referred to as metamaterials, can allow unique light–matter interactions that are not readily possible with most naturally occurring materials. When metals are used, the propagation properties of surface electromagnetic waves that are bound to the metal–dielectric interface can be readily manipulated [1]. Early work on this topic demonstrated that a surface texture on metal film could result in tightly bound surface waves [2]–[4]. More recently, there have been numerous studies that have examined the effects of structuring on metals that are modeled as perfect electrical conductors (PECs), which normally cannot support surface electromagnetic waves [5]–[11]. With appropriate structuring, the effective dielectric properties of the resulting effective medium can be altered such that the dispersion properties mimic those of surface plasmon-polaritons (SPPs). Correspondingly, the medium exhibits an effective plasma frequency that is shifted to low frequencies, typically terahertz (THz) frequencies, and determined by the geometrical properties of the structuring. Since metals in the far infrared and beyond are highly conductive [12], this is a reasonable approximation. It is important to note, however, that metals exhibit finite conductivity at THz frequencies and are able to support surface electromagnetic waves even in the absence of any structuring and that the propagation properties appear to behave the same as SPPs at optical frequencies [13]–[15].

We have previously demonstrated that a one-dimensional (1D) array of rectangular apertures that completely perforate a planar metal film can be used to create a variety of guided-wave devices [16, 17]. The effective dielectric properties of the perforated metal are altered, as discussed above, with the effective plasma frequency that corresponds to the cutoff frequency of the rectangular aperture. Using this approach, we have fabricated a number of guide-wave devices, including a straight waveguide, a Y-splitter and a 3 dB coupler. While the approach is promising for developing other types of guided-wave structures, it has two significant limitations. Firstly, since the apertures completely perforate the metal film, the propagating modes travel along both the top and bottom metal surfaces. Since the excitation and subsequent detection take place on one side of the metal film, the propagating modes on the other surface constitute an effective loss. Secondly, the devices that have been demonstrated so far have all been passive devices. One approach to creating active devices involves filling the apertures, which is technically challenging with through holes.

A solution to both these issues involves using blind holes (i.e. holes that do not completely perforate the metal film) instead of through holes. Prior to our work on guided-wave devices, Williams et al [18] demonstrated a plasmonic slab waveguide based on a 2D periodic array of square blind holes. In that work, they observed broadband surface wave propagation up to the band edge, with a corresponding reduction in the out-of-plane confinement. The broadband propagation that they observed arose from the fact that the cutoff frequency of the square blind holes lay beyond the Bragg frequency. Furthermore, conventional microfabrication techniques typically limit the aspect ratio (hole depth to hole width) to less than one. The combination of these two issues can limit the extent of curvature observed in the corresponding dispersion curves.

In this paper, we experimentally demonstrate the ability to obtain wavelength-scale spatial confinement and low-loss guided-wave propagation of THz radiation using 1D arrays of periodically spaced rectangular blind holes in metal films. The cutoff frequency associated with...
with each of the rectangular structures is designed to lie well below the corresponding Bragg frequency. We also vary the depth of the holes from a value slightly less than the width of the aperture to four times as deep as the aperture width. Using a simple effective cavity resonance model and finite-difference time-domain (FDTD) simulations, we explain the origin of the various modes. In order to measure the mode propagation properties, we use THz time-domain spectroscopy, which allows us to directly measure the spectral amplitude and phase of the THz electric field. The technique can also be used to measure the complete vector nature of the THz surface electric field directly as well as map out its spatial distribution [15]. We use this capability to measure the modal confinement and loss properties of a straight waveguide. Finally, we use the results to design, fabricate and characterize a \( Y \)-splitter. This approach offers a straightforward path for developing active THz guided-wave devices.

2. Experimental details

We used a modified THz time-domain spectroscopy setup to characterize the guided-wave properties of blind-hole-based devices. Details of the experimental setup have been discussed in detail elsewhere [15]. However, for completeness, we give a brief discussion here. An amplified Ti:sapphire femtosecond laser served as the optical source, which was split 80 : 20 to yield the optical pump and probe beams, respectively. The optical pump beam illuminated a 1 mm thick \( \langle 110 \rangle \) ZnTe emitter and the resulting broadband THz radiation was collimated and normally incident onto a semi-circular groove etched into each device. After propagation along the surface, the THz SPPs were measured using a second 1 mm thick \( \langle 110 \rangle \) ZnTe crystal via electro-optic sampling. Because of the crystal orientation and the polarization of both the optical probe and THz SPP beams, we were only sensitive to the \( E_z \) component of the surface field. By moving the optical probe beam and electro-optic crystal simultaneously relative to the surface of the patterned structure, we were able to measure the spatial distribution of the THz electric field at any point along and above the surface, as well as the loss properties of the propagating modes. We note that we did not observe any cavity tuning based on the location of the electro-optic probe crystal.

We fabricated a number of guided-wave structures using a multistep process. Firstly, using a planar stainless steel foil with a thickness corresponding to the desired blind hole depth, between 140 and 635 \( \mu m \), we fabricated a 1D array of periodically spaced rectangular apertures that completely perforated the metal film. The apertures were made using standard laser micromachining techniques. We then glued the foil to a second planar stainless steel foil using a dry epoxy film. Finally, we sputter deposited approximately 400 nm of Al over the composite structure. Sputter deposition ensures that all the surfaces within the blind holes are coated. We have previously shown that once the metal thickness is greater than approximately two skin depths (\( \delta \sim 150 \text{nm} \) at THz frequencies), the properties of the surface waves are determined by the properties of the top metal film [19]. We measured the depth of the holes using standard profilometry to ensure that the epoxy did not reduce the effective depth of the holes.

In figure 1, we show a schematic diagram of a typical guided-wave structure, along with the corresponding excitation and detection scheme and blind hole dimensions. A 1 cm diameter, 300 \( \mu m \) wide and 100 \( \mu m \) deep semi-circular groove was etched into the top metal film with the origin lying at the position of the first blind hole. The groove coupled and focused normally incident broadband THz radiation into the waveguide. We have previously shown that a
Figure 1. (a) Schematic drawing of the planar THz waveguide, including the excitation and detection scheme. The optical probe beam propagated parallel to the waveguide modes. A (110) ZnTe crystal was used for coherent detection of the $E_z$ component of the guided wave. (b) The geometrical parameters of the device include hole length, $s$, hole width, $a$, hole depth, $h$, and center-to-center hole spacing, $d$. In all the structures, we used $s = 500 \mu m$, $a = 150 \mu m$, and $d = 250 \mu m$ and $h$ could vary between 140 and 635 $\mu m$. The semi-circular groove at the input end is used to couple normally incident broadband THz radiation to SPPs.

A semi-circular groove acts to strongly focus the coupled surface field [20] at the origin of the semi-circle, which coincides with the location of the first blind aperture. We have found this to be the most efficient means for coupling broadband THz radiation to these structures. In all the structures discussed below, the rectangular blind holes had dimensions of $s = 500 \mu m$, $a = 150 \mu m$, $h = 140–635 \mu m$ and $d = 250 \mu m$, as shown schematically in figure 1(b). Compared to the wavelength ($\lambda$) of the lowest-order mode, discussed below, the aperture width is $\sim \lambda/6$ and the periodicity is $\sim \lambda/4$, indicating that we are operating in the long-wavelength limit.

The waveguide properties and dispersion relations were simulated using the FDTD technique. The metal was modeled as a PEC with air as the surrounding dielectric medium. We used a spatial grid size of 10 $\mu m$, which was sufficient to ensure convergence of the numerical
calculations, and perfectly matched layer absorbing boundary conditions for all boundaries. In the simulations, a z-directed dipole was used as the broadband excitation source and was placed on the metal surface at one end of the rectangular array. The $E_z$ component of the surface field was sampled at various points along the waveguide using a non-perturbative electric field probe.

3. Experimental results and discussion

We begin by examining the spectral transmission properties of these devices. In figure 2, we show the experimentally measured and numerically simulated waveguide transmission spectra measured at the end of several 5 cm long linear waveguides with blind holes of depths $h = 100$, 140, 370 and 635 $\mu$m. There are a number of notable features in these spectra. When the holes are very shallow (i.e. 100 $\mu$m deep or less), the waveguide transmission spectra appear to be relatively broadband, albeit with a clear high-frequency cutoff. As the hole depth begins to increase, both the linewidth and cutoff frequency of this resonance decrease. As the hole depth increases further, the single transmission resonance is replaced by multiple narrowband transmission resonances. In all the spectra, it is apparent that no modes appear at frequencies above $\sim 0.6$ THz. This corresponds to the Bragg frequency $f_B = c/2d$, where $c$ is the speed of
light in vacuum and \( d = 250 \, \mu \text{m} \). Any propagating mode with a transverse wave number beyond the first Brillouin zone will exhibit high propagation loss.

In comparing the experimental and simulated spectra, it is clear that they have very similar features, i.e. while the resonance peaks do not necessarily occur at the same frequencies, the anti-resonance (AR) frequencies (i.e. the frequencies corresponding to the sharp dips on the high-frequency side of each resonance in the experimental data and the frequencies corresponding to extrapolation of the trailing edge of each resonance in the simulated data) appear to match. It should be noted that while sharp AR dips are not apparent in the simulations shown in figure 2, they are clearly evident in simulations using rectangular through holes \([16, 17]\). Although further work is necessary to understand this difference, AR dips have been shown to arise in the transmission properties of such structures because of a Fano interference phenomenon \([21]\).

This interest in AR frequencies arises because they are the relevant parameter, not the frequencies associated with the resonance peaks. To demonstrate this, we have previously shown that as the aperture width, \( a \), is varied, the peak of the lowest-order resonance shifts slightly, but the corresponding AR frequency remains fixed. This was also observed in the transmission properties of 2D arrays of subwavelength apertures \([22]\). The locations of the AR frequencies can be viewed as effective cavity resonance frequencies of the individual apertures \([23]\) and are approximately given by

\[
\nu_{mnp} = \frac{c}{2\pi} \left[ \left( \frac{m\pi}{s} \right)^2 + \left( \frac{n\pi}{a} \right)^2 + \left( \frac{p\pi}{h} \right)^2 \right]^{1/2},
\]

where \( m, n \) and \( p \) are integers (\( m = 1, 2, 3, \ldots \) and \( n, p = 0, 1, 2, \ldots \)). The lowest-order AR frequency would normally be indexed as \( m = 1, n = 0 \) and \( p = 0 \), so that \( \nu_{100} = c/2 \, s = \nu_c \) (i.e. the cutoff frequency of the rectangular aperture). Since the effective plasma frequency of the effective medium was given by the cutoff frequency of the apertures, we referred to the lowest-order resonance as the plasmonic mode. The energy associated with the mode was highly confined near the surface, with the field decaying evanescently within the apertures. The higher-order modes corresponded to dielectric slab modes, where energy flowed into the apertures and bounced back and forth between the interfaces like Fabry–Perot resonances.

Returning to figure 2, we initially consider only the lowest-order resonance. The corresponding AR frequencies for these structures occur at 0.48 THz \((h = 100 \, \mu \text{m})\), 0.40 THz \((h = 140 \, \mu \text{m})\), 0.32 THz \((h = 370 \, \mu \text{m})\) and 0.31 THz \((h = 635 \, \mu \text{m})\). Clearly the lowest-order mode designation discussed above \((m = 1, n = 0, p = 0)\) will not work. More generally, if we consider waveguides fabricated using blind holes, as \( h \to 0 \), the metal would no longer be structured and could not support a guided-wave mode. Thus, the hole depth, \( h \), must play a role in determining the location of the lowest-order AR frequency (i.e. \( p \neq 0 \)). In order to more carefully understand the depth dependence, we numerically simulated the transmission spectra for waveguides having values of \( h \) between 100 and 635 \( \mu \text{m} \). The AR frequencies associated with the lowest-order mode from both experimental data and numerical simulations are shown in figure 3(a). From the data, it is clear that as the depth of the blind holes increases, the AR frequency asymptotically approaches what we observed for through holes \([16, 17]\). Conversely, as the depth of the blind holes decreases, the AR frequency increases rapidly, as expected. The solid line is a fit to equation (1) with \( p = 0.25 \). Thus, the correct mode assignment for the lowest-order mode is \((m, n, p) = (1, 0, 0.25)\). For a true cavity mode, we would expect that \( p \) would only take on integer values. However, since the top of each rectangular blind hole is open to air, this is not a required constraint.
Figure 3. (a) Experimentally measured (black squares) and numerically simulated (red circles) AR frequencies associated with lowest-order resonance as a function of blind hole depth, with $s = 500 \mu m$, $a = 150 \mu m$ and $d = 250 \mu m$. The solid line is a fit to the data using equation (1) with $m = 1$, $n = 0$ and $p = 0.25$. (b) Experimentally measured out-of-plane $1/e$ decay length of the lowest-order mode as a function of blind hole depth. The solid line is an exponential fit to the data. (c) Dispersion properties of the lowest-order mode as a function of blind hole depth.

At this point, it is worth commenting on the results presented here and those that have been published earlier \cite{18}. In the previous work, the fact that the blind holes were square corresponded to a cutoff frequency (i.e. the AR frequency associated with the lowest-order mode) that lay beyond the Bragg frequency. Thus, Williams and co-workers observed a broad transmission spectrum that abruptly stopped at the Bragg frequency. By using rectangular apertures of sufficient depth, we are able to shift the AR frequency of the lowest-order mode to a value that lies below the band edge. It is important to note that both conditions are necessary. Firstly, by making $s > d$, the cutoff frequency for a rectangular through hole lies below the Bragg frequency. In the case of blind holes, we are further required to make sufficiently deep blind holes. For the specific case of $s = 500 \mu m$, $h$ is required to be $> 72 \mu m$ in order for the lowest-order AR frequency to lie below the Bragg frequency.

Associated with the change in the AR frequency of the lowest-order mode, we would expect that the out-of-plane confinement would also vary with the depth of the blind hole.
As noted earlier, we are able to measure the out-of-plane extent of the surface field by simultaneously moving the optical probe beam and electro-optic crystal relative to the surface of the patterned structure. In figure 3(b), we show the 1/e decay length of the \(E_z\) component of the lowest-order mode. It should be noted that for \(h < 270 \mu m\), the lowest-order mode was not well confined to the waveguide (i.e. the cross-sectional mode width increased along the guide length). For \(h = 635 \mu m\), the 1/e decay length is 1.87 mm. This is very close to the value of 1.69 mm observed with rectangular through holes [16, 17]. As \(h\) decreases, the 1/e decay length increases in a manner that is consistent with earlier observations (i.e. the 1/e decay length at \(\sim 0.3\) THz, corresponding to \(\lambda = 1\) mm, for an unstructured planar metal film was \(\sim 4–5\) mm or \(\sim 4–5\lambda\) [15]). Another way of looking at the modal confinement is by considering the dispersion properties of the blind hole waveguides as a function of hole depth, as shown in figure 3(c). Increased curvature in the dispersion properties for increasing values of the lateral propagation constant should correspond to smaller values of the out-of-plane 1/e decay length.

We are now in a position to examine the higher-order modes. This is most easily accomplished by considering the spectra associated with \(h = 635 \mu m\) (figure 2(d)). The AR frequencies for the three resonances are located at 0.31, 0.43 and 0.58 THz. Numerically, it appears that equation (1) correctly predicts these frequencies if we assign them to (1, 0, 0.25), (1, 0, 1.25) and (1, 0, 2.25), respectively. Thus, the index \(p\) appears to have a constant offset of 0.25. In fact, this appears to be true for all the measured spectra. In order to verify these mode designations, we performed FDTD simulations using a sinusoidal input at each of the individual AR frequencies and computed the corresponding steady-state electric field distributions. In figure 4, we show false color maps of the total electric field in the \(yz\)-plane. Clearly, the distributions show that the values of \(p\) are approximately correct. As expected, the metal layer at the bottom of each blind hole results in a field distribution that is asymmetric along the \(z\)-axis. We attribute the fact that \(p\) takes on non-integer values to this strong asymmetry in the field distribution. It should be noted that the total electric field distributions in the \(xy\)-plane look nearly identical for all three modes (not shown), corresponding to \(m = 1\) in all three cases.

Next, we examined the propagation properties of the lowest-order mode using a waveguide with a blind hole depth of \(h = 635 \mu m\). In figure 5(a), we show the magnitude of the \(E_z\) field component measured along the length (\(x\)-axis) of the waveguide. From these measurements, we find that the waveguide loss for the plasmonic mode is \(\sim 0.083\) cm\(^{-1}\), corresponding to a 1/e propagation length of 12 cm along the waveguide. It is worth noting that for the waveguide based on through holes, the corresponding 1/e propagation length was 7.6 cm [16, 17]. The longer propagation length in the present devices arises, in part, from the fact that the propagating modes are now restricted to propagating only along the top surface of the metal foil. Thus, half the energy is no longer lost to the bottom surface. However, since the bottom of each hole is now covered with metal, its interaction with the propagating surface wave should correspond to a slight increase in the propagation loss.

In figure 5(b), we show the magnitude of the \(E_z\) field component measured along the \(y\)-axis of the waveguide at two different positions along the waveguide, 2 and 4 cm from the waveguide input. The lateral field distributions for the two cross sections exhibit a Gaussian mode profile with a full-width at half-maximum (FWHM) width of 2.8 mm. The fact that the FWHM width is unchanged along the waveguide demonstrates tight confinement of the mode as it propagates along the waveguide. This value is only slightly larger than that measured for the waveguide with rectangular through apertures (~2.2 mm). While the lateral width is only
Figure 4. Total electric field distributions in the yz-plane corresponding to the (a) (1, 0, 0.25), (b) (1, 0, 1.25) and (c) (1, 0, 2.25) modes for $h = 635 \mu$m. An expanded view of the color scale is shown below (c). In each case, the aperture length, $s$, along the y-axis is 500 $\mu$m and the depth, $h$, along the z-axis is 635 $\mu$m.

$\sim 3\lambda$ (for a lowest-order resonance at $\sim 0.3$ THz, $\lambda = 1$ mm), this value is larger than expected from numerical simulations.

The strong interest in plasmonic structures arises, in part, from the possibility of obtaining subwavelength spatial resolution and, in the case of guided-wave devices, subwavelength cross-sectional modal areas. Clearly, the lateral width observed in figure 5(b) and the corresponding 1/e decay length found in figure 3(b) are greater than the corresponding wavelength. In order to probe this issue further, we used FDTD simulations to calculate the magnitude of the $E_z$ field component along the y-axis of the waveguide, as shown in figure 5(c). Simulations which assume that the metal behaves as a PEC with idealized geometrical parameters yield an FWHM lateral width of 0.48 mm, corresponding to $\sim 0.5\lambda$. There is a similar correspondence between the out-of-plane 1/e decay length computed from FDTD simulations and the actual values measured experimentally (figure 3(b)). These results clearly show that while idealized parameters can yield subwavelength mode properties, the use of real metals with practical fabrication conditions yields experimentally measured mode properties that are generally larger.
Figure 5. Propagation properties of the waveguide with $h = 635 \mu$m. (a) Field amplitude $|E_z|$ measured along the $x$-axis for the lowest-order mode (filled circles). The line is an exponential fit to the data. (b) $|E_z|$ field amplitude measured along the $y$-axis at two different positions along the waveguide: 2 and 4 cm from the waveguide input (filled circles). The lines are Gaussian fits to the data. $Y = 0$ corresponds to the center of the waveguide. (c) $|E_z|$ field amplitude computed from FDTD simulations (filled circles), where the metal was modeled as a PEC with idealized geometrical properties. The line is a Gaussian fit to the data. $Y = 0$ corresponds to the center of the waveguide.

Finally, based on the guided-wave properties discussed above, we fabricated a simple $Y$-splitter to demonstrate the utility of this approach in developing useful device capabilities. The splitter, shown in the upper panel of figure 6, consists of a 10 mm long input arm, two 60 mm long arms slanted at an angle of $11.2^\circ$ from the input and two 20 mm long output arms that were parallel to the input arm. We measured the magnitude of the $E_z$ component of the guided-wave electric field along the $y$-axis at the output of this device, as shown in the lower panel of figure 6. The data were fit to the sum of two spatially offset Gaussian functions with peaks occurring at the center of the two output waveguide arms at $-10$ and $+10$ mm. The FWHM widths of the two Gaussian functions are each 2.7 mm, which is in good agreement with the mode size shown in figure 5(b). In addition, the measured contrast ratio between peak amplitude and background signal was $\sim 3.7 : 1$. 

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Figure 6. Passive guided-wave Y-splitter fabricated using linear periodic arrays of rectangular blind holes ($h = 635 \, \mu m$). Upper panel:— schematic diagram of the Y-splitter structure; a semi-circular groove is used to couple free-space THz radiation into the guiding structure. For clarity, the splitter section of the Y-splitter is expanded in the figure panel. Lower panel: field amplitude $|E_z|$ measured along the y-axis at the end of the Y-splitter (red dots), marked as a black dashed line in the upper panel. The red trace is a fit to the experimental data using a sum of two spatially offset Gaussian functions.

4. Conclusion

In conclusion, we have designed, fabricated and characterized a planar THz waveguide technology based on a 1D array of periodically spaced blind holes. The devices are fabricated using a multilayer construction that is critical for enabling blind holes of sufficient depth. We find that the mode properties depend sensitively not only on the length of the rectangular holes, but also on the depth. For blind holes that are less than $\sim 270 \, \mu m$, the propagating modes are
not well confined to the waveguide. With increasing blind hole depth, the level of confinement increases. Thus, for blind holes with a depth of 635 µm, we find that the waveguide modes are tightly confined to the guiding structure with a 1/e propagation length of ∼12 cm. Using this information, we demonstrate the efficacy of this approach by fabricating and characterizing a Y-splitter. The approach opens exciting new avenues for both passive and active THz guided-wave devices and circuits.

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