Research article

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High-performance and compact broadband terahertz plasmonic waveguide intersection

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Abstract: For terahertz (THz) integrated systems, an intersection between waveguides is inevitable and is often accompanied by considerable crosstalk and loss. Here, we propose and experimentally demonstrate a novel type of crossing with a footprint less than $0.2 \times 0.2 \text{ mm}^2$ for THz surface plasmon polariton waveguiding. With an optimized crossover structure, the measured loss of the intersection is as low as 0.89 dB/crossing, and the crosstalk is less than $-19.06 \text{ dB/crossing}$ at 0.55 THz. The proposed crossing structure is compact and has low loss and crosstalk within a broad band, which will pave the way for a wide range of new applications for THz integrated systems.

Keywords: terahertz near-field; terahertz spoof surface plasmon polaritons; surface waves; waveguide intersection; crosstalk.

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1 Introduction

Compact and multifunctionally integrated systems are an important direction for the development of terahertz (THz) science and technology. With the help of surface plasmon polaritons (SPPs), which are electromagnetic waves propagating along a metal/dielectric interface [1], the electromagnetic field can be localized and thus manipulated at the subwavelength level. Because metals behave close to perfect conductors at THz frequencies, high confinement of SPPs at flat metal surfaces cannot be achieved [2, 3], so that many applications of SPPs cannot be extended directly in this frequency range. To solve this problem, the concept of spoof SPPs was proposed by Pendry et al. [4, 5]. Spoof SPPs are surface-confined electromagnetic waves supported by periodic metallic structures in the perfect-conductor limit, which resemble the SPPs at a metal-dielectric interface in the optics regime in terms of field confinement and dispersion characteristics [4–6]. This concept opens up an effective way to route SPPs on planar geometries at THz frequencies [6]. THz spoof SPP waveguides can provide sub-wavelength confinement and enable low loss transmission of THz waves over long distances in a specific direction. So far, waveguiding structures for THz spoof SPPs based on periodic grooves or pillars have been proposed [7–11] and demonstrated [12, 13]. With these waveguide components, some basic functions could thus be achieved, such as straight waveguiding, S-bend waveguiding, Y-splitting, and directional coupling [13]. Further development of THz plasmonic circuitry requires more fundamental components with miniaturization and multifunctionalities. Among them, the intersecting waveguide is a vital one for high-density integration [14–19].

However, intersecting waveguides based on spoof SPPs in the THz regime have rarely been reported. For optical waveguides, the number of optical waveguide intersections in large-scale integration can be as large as hundreds [20–22]. To solve and improve the waveguide crossing performances, various schemes have been proposed, including optimization of the crossing angle [23], adiabatic

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mode expanders [24, 25], metamaterials [26], mode field conversion [27], wavefront matching [28, 29], bridge structures [30], and resonators [31]. Photonic crystal resonators exploiting photonic crystal cavities to enhance coupling through the intersecting waveguides [32] have been optimized [33] and fabricated [34]. This method requires stringent periodicity and small feature sizes, so it is vulnerable to manufacturing defects. Multimode interference structures based on self-imaging the waveguide mode field from the waveguide input plane to its center and output planes have been reported [35–38]. However, the abovementioned crossing structures occupy relatively large footprints or suffer from narrow bandwidth, and complex optimization processes are needed in the design and fabrication. Subwavelength grating waveguides are also considered as an effective crossing to minimize the loss and suppress the crosstalk [39]. The polarization-dependent loss of the grating structures has also been experimentally studied [40]. Although these studies provide different solutions to the waveguide-intersecting problem, most of them focus on dielectric waveguides for optics. It is still a great challenge to achieve compact, low-crosstalk, and broadband THz spoof SPP waveguide crossings with high performance.

In this paper, we report on the design, simulation, and experimental characterization of a novel THz spoof SPP waveguide crossing with minimized loss and suppressed crosstalk. This compact crossing has a footprint of less than $0.2 \times 0.2 \text{ mm}^2$ (about $0.13\lambda^2$ for $f = 0.55 \text{ THz}$) and can be fabricated with other waveguide components on the same platform. By optimizing a crossover structure to suppress the crosstalk, the measured loss can be as low as 0.89 dB/crossing , and the crosstalk can be less than $-19.06 \text{ dB/crossing}$ at 0.55 THz . We also estimate the loss and crosstalk by investigating a set of waveguides with one, two, and

three crossings. In addition, the loss and crosstalk between cross-waveguides are influenced by the crossing angle, and our results show that using a larger-than- 30° angle of the intersection between the cross-waveguides can meet the device design requirements. This kind of plasmonic structure with good functionality will lead to the development of more robust and complex THz integrated systems.

2 Results and discussion

A waveguide intersecting with another creates a region with no lateral mode confinement, resulting in a sudden broadening of the guided waves. The broadening causes loss due to excitation of radiation modes and crosstalk by coupling to the guided modes of the intersecting waveguide [40]. Our goal is to design a novel, compact, and efficient structure for crosstalk suppression in interconnecting THz spoof SPP waveguides.

The structure of the spoof SPP waveguide proposed in this work is presented in Figure 1A, and the whole design with corresponding optical microscopy photos is provided in Supplementary Figure S1. The waveguide consists of a periodic arrangement of metallic pillars arranged on the top of a metallic surface, also known as a domino structure [11, 13], where the pillar width $w = 120 \mu\text{m}$, length $l = 50 \mu\text{m}$, height $h = 80 \mu\text{m}$, and period $p = 100 \mu\text{m}$. We use the commercial software CST Microwave Studio (Dassault Systèmes, Paris, France) to numerically solve the eigenmodes supported by the waveguide. For simplicity, the metal is assumed to be a perfect electric conductor in all our simulations, which is valid for metals in the microwave and THz regimes [11–13].

Figure 1B shows the dispersion relation for the fundamental mode of the waveguide, that is, the relation

Figure 1: Structure and dispersion relation.

(A) Schematic of the proposed structure. The upper left inset shows a close-up of the annular sector-shaped hole array excitation region as well as sector-shaped column array coupling region, and the upper right inset shows the waveguide structure with the following geometrical parameters: $w = 120 \mu\text{m}$, length $l = 50 \mu\text{m}$, height $h = 80 \mu\text{m}$, and period $p = 100 \mu\text{m}$. (B) Dispersion relation of SPP modes for one row of metal pillars with different widths of 40, 60, 80, 100, and $120 \mu\text{m}$.

between the propagation constant k_x and frequency. The width of the metallic pillar w is varied from 40 to 120 μm to investigate its effect on the surface wave propagation. As can be seen from Figure 1B, SPP modes can be supported and propagate along the surface of the metal structure above 0.4 THz. However, at around 0.7 THz, the group velocity of the SPP mode begins to gradually decrease toward zero at the first Brillouin zone boundary ($k_x = \pi/p$). The important point to note is that although the cutoff frequency becomes smaller when the width is increased from 40 to 120 μm , the dispersion relation of the SPP mode is generally insensitive to the width.

Waveguide crossings are first simulated by means of the time domain solver of CST. As the propagation constant of SPPs is greater than the wave vector in the dielectric, the dispersion curve therefore lies to the right of the light line of the dielectric, and excitation by free-space light is not possible unless special techniques for phase-matching are employed [1]. To couple free-space THz radiation and excite the SPPs, an arc-shaped curved hole array on the thin metal is adopted in both the simulations and experiments [41, 42], as shown in the upper left insert of Figure 1A. The metal arc-shaped curved hole array can provide an additional wave vector component to satisfy the wave vector matching condition between the incident electromagnetic wave and the SPPs. Curved holes with a width of 40 μm are arrayed with a period of 400 μm along the radial direction. For a high coupling efficiency, the center of each annular sector coincides with the position of the first rectangular cylinder of the waveguide. The innermost and outermost radii of the annular sector region are 2220 and 3820 μm , respectively, and the central angle is 60°. The hole arrays are separated into small holes by several metal strips, which have a width of 50 μm and angle of 5°. In order to effectively excite the SPPs and prevent the transmitted wave from being coupled directly into the waveguide, the THz wave is normally incident from the bottom surface of the sample to the excitation grating region in the z -direction, and the THz spot covers the entire excitation region. The condition to excite SPPs should ensure that the direction of the linearly polarized THz wave is perpendicular to the hole gratings as well as parallel to the propagation axis of the waveguide. Furthermore, a fan-shaped funnel structure consisting of pillars is designed to efficiently couple the SPPs to the waveguide [13, 43]. In this design, the period of the pillars in the funnel structure is reduced gradually. The methods of excitation and the funnel structure are applied in all waveguide components.

First, a direct crossing (that is, two perpendicular waveguides intersect directly) and a tapered crossing (that

is, two width-graded waveguides intersect) are studied under the same conditions as a comparison with our low crosstalk crossing. The structure diagrams of the direct and tapered crossings are shown in Figure 2A and B, respectively. The parameters of the metallic pillars are the same as those described above except that the width of the pillars in the taper section for the taper crossing is gradually reduced from $w_a = 120 \mu\text{m}$ to $w_b = 60 \mu\text{m}$ over seven grating segments. Cylinders with a diameter $d = 50 \mu\text{m}$ are used in the tapered crossing to help achieve a smaller mode size and lower crosstalk. As the effective index of the SPP mode is rather insensitive to the lateral width, as shown in Figure 1B, a compact taper is able to laterally compress the mode size down as also shown in [11], where the mode size is defined as the FWHM of the modulus of the Poynting field distribution. The simulated results of the electric field distributions corresponding to the two components at 0.55 THz are displayed in Figure 2D and E, respectively. Obviously, for the direct crossing, strong electric field can be observed on the cross-waveguide. Although the crosstalk has been reduced in the tapered waveguide, there is still considerable field distribution in the cross-waveguide.

In order to reduce loss and suppress crosstalk, a novel THz spoof SPP waveguide crossing is presented in Figure 2C. This is done by both gradually tapering the waveguide width near the cross-section as in Figure 2B and using a structure composed of cylinders with the same parameters as those for the tapered crossing to confine the mode. For the low-crosstalk crossing structure proposed here, four cylinders closest to the central one are rotated 45° with respect to it. The simulated electric field distribution in Figure 2F shows the excellent crosstalk suppression performance of the structure. Figure 2G–I illustrate the vector electric fields corresponding to the three structures. As can be seen in Figure 2H, reducing the waveguide width as the THz wave propagates along the crossing reduces the mode size near the crossover point. As the use of the cylindrical structure at the taper end reduces the coupling loss and suppresses diffraction, radiation modes are effectively reduced. However, because of the same distance existing between the cylinders, the electric field on the central cylinder can easily be coupled to the cylinders of the intersecting waveguide, resulting in a large crosstalk, as explained in Supplementary Figure S2.

According to the coupled mode theory, the amount of energy transfer between these two coupled waveguides depends critically on the coupling strength, which is in turn dependent on the distance between the coupling components. Therefore, the goal of our design is to maximize the distance between the transmission waveguide

Figure 2: Performance comparison of three crossings by simulation.

Structure diagrams of three cases investigated: (A) direct crossing, (B) tapered crossing, and (C) low crosstalk crossing. (D–F) Simulated electric field distributions corresponding to (A–C) in a horizontal plane slightly above (at $100\ \mu\text{m}$) the surface of each structure at $0.55\ \text{THz}$. (G–I) Corresponding vector electric fields represented by the arrows, and color scales of the arrows indicate the field amplitudes. (J) Loss and (K) crosstalk as a function of frequency for direct crossing (dotted line), tapered crossing (dashed line), and low crosstalk crossing (solid line), respectively.

and the cross-waveguide without adding additional structures and materials. By reasonably rearranging the four cylinders around the central cylinder and controlling their distance in the proposed design, the coupling of the electric field to the intersecting waveguide can be suppressed

successfully, and the structure can maintain its symmetry at the same time, as shown in Figure 2I and Supplementary Figure S2. An animation is provided in Supplementary Figure S3 for a comparison of the performances of the three cases investigated. It should be pointed out that

the intersecting structure has the same parameters, while the central segment is symmetrical to ensure an identical geometry for both waveguides. After the crossing point, an identical geometry is used for field transition back to the original waveguide. The footprint of the crossing is only $0.2 \times 0.2 \text{ mm}^2$ (about $0.13\lambda^2$ for $f=0.55 \text{ THz}$), and the structure does not require additional materials and processing technology and can be fabricated simultaneously with the waveguides.

Figure 2J and K show the calculated loss and crosstalk as a function of frequency for the three cases, respectively. The loss is calculated as the ratio of the power coupled to the fundamental mode of the input waveguide to the output power: $\text{Loss} = 10 \log(P_{\text{Input}}/P_{\text{Output}})$, whereas crosstalk is calculated as the ratio of the power coupled to the fundamental mode of the intersecting waveguide to the input power: $\text{Crosstalk} = 10 \log(P_{\text{Crosstalk}}/P_{\text{Input}})$. Because in this analysis the metal is assumed lossless, radiation and crosstalk are the only source of loss. The loss of the crossing is extracted by comparing the insertion loss of the structure with that of a straight waveguide of the same length. In other words, the difference in insertion losses of the crossing and the straight waveguide is attributed to the loss of the crossing. The power is obtained by integrating the longitudinal component of the Poynting vector in perpendicular planes located near the input of the waveguide and exit sides of the two waveguides. It can be seen that the direct crossing (dotted line) has high loss and crosstalk because of the excitation of radiation modes and coupling to the intersecting waveguide. For the tapered crossing structure (dashed line), the loss and crosstalk are reduced because of the reduction of mode size and suppression of diffraction. However, at higher frequencies, coupling is increased to the intersecting waveguide mode,

which leads to a larger crosstalk. Compared with the previous two structures, the low crosstalk crossing (solid line) has lower loss and crosstalk in a wide frequency range: the loss is less than 0.8 dB below 0.62 THz, and the crosstalk is less than -15 dB in the whole SPP transmission range. Minimum loss of 0.15 dB and crosstalk of -29.26 dB can be obtained at 0.61 and 0.64 THz, respectively.

For an experimental demonstration of our proposed strategy, high-quality waveguides are fabricated by optical lithography on a silicon substrate, followed by deep reactive ion etching. A 200 nm thick gold film is then coated on the chip, including the sidewalls of the pillars in a gold sputter coater. Figure 3A shows a scanning electron microscopy (SEM) image of the fabricated crossing. The scanning area is $2 \times 2 \text{ mm}^2$, and the excitation area and funnel structure are not taken into account. The inset in Figure 3A shows the detail of the crossing region.

The fabricated intersecting waveguide components are then experimentally characterized by using a fiber-optic scanning near-field THz microscopy system operating at 1550 nm [12, 13], as illustrated in Figure 3B. The light source is a 1550 nm femtosecond fiber laser, where the output is split into two beams by a beam splitter. The beam used for detection passes through a piece of fiber and is back-coupled into free space to be focused on a probe. The probe is based on low-temperature-grown GaAs. As the laser light with a wavelength of 1550 nm cannot excite the carriers in GaAs, a frequency doubling module is used to convert the light at 1550 to 780 nm. The other beam is connected to a photoconductive antenna fabricated on an InGaAs/InAlAs substrate through an optical fiber delay line to generate the THz radiation. The THz wave is finally focused on the sample to excite the SPPs. The sample is attached to a three-dimensional translational sample holder, and the probe is

Figure 3: Crossing image and experimental system.

(A) SEM image of the crossing. The inset shows the detail of the crossing region. (B) Illustration of experimental setup. BS, Beam splitter; FDL, fiber delay line; FDM, frequency doubling module; 3-D TSH, three-dimensional translational sample holder; 2-D TD, 2-dimensional translational detector; CDA, current dumping amplifier; QWP, quarter-wave plate; and LIA, lock-in amplifier.

moved in the x - and y -directions with a two-dimensional translational detector. In the experiment, we focus the THz waves on the excitation area of the sample, and then the excited SPPs are detected by a near-field probe with a resolution of $8\ \mu\text{m}$. The THz probe is placed above the sample at a distance of $100\ \mu\text{m}$, and the signals are scanned point by point with a step of $200\ \mu\text{m}$ along the x -direction and a step of $100\ \mu\text{m}$ along the y -direction. The probe collects the electrical signal via a current dumping amplifier and lock-in amplifier and sends the collected time domain signal to the computer for data processing. Finally, the performance of the waveguides is characterized by mapping the near-field distribution above the waveguide surface.

We first estimate the loss and crosstalk by studying a sequence of waveguides with one, two, and three crossings, as shown in Figure 4A–C. The distance between two intersecting waveguides is equal to the length of two tapered transition regions ($2100\ \mu\text{m}$). Figure 4D–F show the simulated normalized power $|E_z^2|$ distributions at $0.55\ \text{THz}$ for one, two, and three crossings, respectively. Clearly, this

structure enables a high-quality transmission and crosstalk suppression for both single-waveguide and multi-waveguide crossover systems. Figure 4G–I show the corresponding measured images, which are in good agreement with the simulations. In Figure 4J–L, the cross-sectional normalized power distributions are displayed at the intersecting waveguide positions as indicated by the dotted lines in the corresponding figures of Figure 4G–I and also the values of the x -coordinates. For the recorded cross-sectional field distributions, the fields are strongly concentrated near $y=0$, and the field amplitudes decay quickly to almost zero away from each crossing. The excellent crosstalk suppression performance of this component is thus fully corroborated. Experimental characterization of the crossings demonstrates that for a single crossing, the loss is as low as $0.89\ \text{dB/crossing}$ and the crosstalk is less than $-19.06\ \text{dB/crossing}$ at $0.55\ \text{THz}$. The mode diffraction is thus effectively suppressed by the four rotated cylinders around the central cylinder. Meanwhile, with narrower taper widths, the mode is more localized, and the crosstalk is expected to decrease further.

Figure 4: Performance of one, two, and three crossings.

(A–C) Structure diagrams of one, two, and three crossings. (D–F) Simulated and (G–I) experimental results for normalized power $|E_z^2|$ distributions corresponding to one, two, and three crossings, respectively, in a horizontal plane slightly above (at $100\ \mu\text{m}$) the surface of each structure at $0.55\ \text{THz}$. (J–L) Cross-sectional normalized power distributions at the corresponding intersecting waveguides in (G–I).

The measured loss is calculated as the difference between the insertion loss of the structure and transmission loss of the straight waveguide with the same length, and the crosstalk is estimated by measuring the powers at the taper beginning of the transmission-waveguide and at the taper end of the intersecting waveguide for each cross-section. This calculation method is to minimize the influence of the propagation loss. As most of the energy of the

SPPs is localized on the waveguide surface and the electric field component E_z is much larger than the other components, the intensity of E_z is approximately proportional to the energy flux density. The power of the SPPs is thus obtained by integrating the simulated normalized power $|E_z^2|$ near the input and output ports of the waveguides. Using this approach, the loss and crosstalk for each single crossing of the other two structures are obtained and

Table 1: Loss and crosstalk of waveguides with one, two, and three crossings at 0.55 THz.

Number of crossings	Scanning area (mm ²)	Simulation		Experiment	
		Loss (dB/crossing)	Crosstalk (dB)	Loss (dB/crossing)	Crosstalk (dB)
One	6.5×5.0	0.27	-15.44	0.89	-19.06
Two	8.0×5.0	0.48	-15.99 / -16.70	1.01	-14.60 / -15.35
Three	9.5×5.0	0.42	-16.19 / -15.75 / -19.35	0.95	-14.05 / -13.08 / -16.40

Figure 5: Performance of the crossing for different angles.

(A) Transmission spectra for different angles considered. (B) Transmission as a function of angle at 0.55 THz. (C–E) SEM images of structures corresponding to 45°, 60°, and 75° crossing angles, respectively. (F–H) Simulated and (I–K) experimental results for normalized power $|E_z^2|$ distributions corresponding to (C–E) in a horizontal plane slightly above (at 100 μm) the surface of each structure at 0.55 THz.

shown in Table 1. The corresponding propagation loss of the straight waveguide is about 1.06 dB/mm. A deterioration of the measured loss values compared with simulation can be attributed to the fabrication error and actual metallic loss neglected in simulation. Notwithstanding the fabrication error, the structure still performs remarkably well, both in terms of crosstalk and loss (Figure 4).

The performance of the cross structure is also affected by the crossing angle, which is defined as the angle between the intersecting waveguide and the transmission waveguide. In order to study the influence of the angle on the structure performance, crossover structures with different angles $\theta = 30^\circ$, 45° , 60° , and 75° are designed. The numerical transmission spectra for the analyzed structures are shown in Figure 5A, where a general trend of decreasing transmission with a decreasing angle of the cross-waveguide can be observed. Figure 5B shows the transmission as a function of the intersection angle at 0.55 THz. The results show that more than 40% transmission can be obtained when using a larger-than- 30° angle of intersection between the cross-waveguides. When the angle decreases, coupling between the waveguides will lead to a rapid deterioration of the crosstalk suppression performance. Cross-waveguides with θ values of 45° , 60° , and 75° are fabricated as illustrated in Figure 5C–E to verify the numerical analysis. In order to reduce the influence of the rotation on the structure performance, the two cylinders at the end of the conical part of the intersecting waveguides are also rotated around the central cylinder. The simulated and the experimental results for the normalized power $|E_z^2|$ distribution corresponding to different θ with a scanning area of $7.5 \times 6 \text{ mm}^2$ at 0.55 THz are compared in Figure 5F–H and I–K, respectively. The results demonstrate good crosstalk-suppression performance throughout the structure at the designed crossing angles.

3 Conclusion

In summary, a novel plasmonic structure enabling suppressed crosstalk between intersecting THz spoof SPP waveguides is theoretically and experimentally demonstrated. The structure shows low loss and good crosstalk suppression for both single-waveguide and multi-waveguide crossover systems within a wide frequency range. A loss of 0.89 dB/crossing and a crosstalk of $-19.06 \text{ dB/crossing}$ have been achieved. The relationship between crosstalk and the crossing angle is also investigated. Because of its features in terms of loss, crosstalk, fabrication tolerance, device size, bandwidth, and so on, we believe that

the waveguide intersection will facilitate large-scale interconnection and minimize the device footprint for future complex planar THz integrated systems.

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