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A long-range hybrid THz plasmonic waveguide with low attenuation loss

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HIGHLIGHTS

- A strong confinement and low loss with propagation lengths exceeding 14 mm at normalized mode areas of 1.72×10^{-2}.
- We showed that a HTSPP waveguide has better performance compared to other conventional HSPP waveguides.
- Our analysis demonstrated how to facilitate the development and design of HTP high-density integrated circuits or bio-sensors.

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ABSTRACT

Numerical solutions are obtained for the proposed novel hybrid terahertz plasmonic waveguide structure, namely the silicon metal silicon (SMS) waveguide. It is shown that the SMS waveguide can overcome the diffraction limit while still maintaining a sizeable propagation length. The geometric dependence of the mode characteristics of this structure is analyzed in detail, showing strong confinement and low loss with propagation lengths exceeding 14 mm at normalized mode areas of 1.72×10^{-2}. By using the FEM method (Comsol), the guiding properties of the hybrid terahertz surface plasmon polariton (HTSPP) waveguide are numerically analyzed at the THz frequency, and a combination of double-structured comparisons of the best features of the terahertz plasmonic waveguide is made. Depending on the height used and how the mode confinement is measured, various modal designs, such as double microwire structures, are developed. The structures indicate that we verified the possibility of low attenuation loss of hybrid THz plasmonics propagation. The effective mode area A_{eff}, energy distribution, and propagation length L_p versus height for waveguides with Si microwire and SiO_2 are shown. The numerical calculation results reveal a potential for use in applications such as optical force in trapping and transporting biomolecules, and in high-density integrated circuits.

1. Introduction

There has been significant growth recently in theoretical and experimental work related to Hybrid Plasmonic Waveguides (HPW). The research studies have explored the plasmonic phenomenon within a low index nanogap between a high index waveguide and a conducting substrate. Numerous groups are presently investigating the interaction between a free carrier concentration and an electromagnetic field [1–3] giving rise to well-known surface plasmon polaritons (SPP). These can be used to confine light and increase electromagnetic fields at an interface between two media where at least one is conducting [4].

The plasmonic waveguide is a good candidate for achieving large degrees of confinement and practical propagation lengths [5]; hence, sub-wavelength waveguides have been realized in various geometries for the next generation of integrated photonic circuits (IPC) [6–9]. Different structures have been proposed [10,11] in the optical range. For example, in [10], the hybrid mode is shown to be strongly confined even in sizes smaller than 100 times the area of a diffraction-limited spot. Large subwavelength mode confinement in [11] shows that a strong interaction between a dielectric cylindrical waveguide mode and a long-range surface plasmon polaritons (LRSPP) mode of a thin metal film can be obtained.

It should be pointed out that the structure design in [10] was chosen primarily for optical frequency wavelength, which enabled the researchers to control the light in a small area over a typical propagation length (434 μm), albeit without the inclusion of hybrid plasmonics in the THz regime. We therefore wish to take this a step further by including the hybrid THz contribution in the SPP waveguide. THz frequency shows great promise for use

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in high-resolution imaging, spectroscopy, and security applications such as biological agents or explosives [12]. A unique feature shown in [13] is the interaction with the material in ways that are diverse from other forms of electromagnetic radiation. For instance, plastics and papers are transparent to terahertz frequencies [14]. Various structures have been proposed as plasmonic waveguides in the THz range [15,16].

Less attention has been paid, however, to a hybrid plasmonic terahertz (THz) waveguide (HPTWG) supporting hybrid plasmonic modes traveling through the microscale of a lossy material to achieve high mode confinement. The frequency of a THz wave occupies the electromagnetic spectra between microwave and infrared ranges [16]. To take advantage of this phenomenon, HPTWG has been the subject of much recent research [6,9,16].

Hybrid terahertz SPP can achieve high mode confinement in terms of longer amplitude propagation lengths [16] by merging the merits of an SPP waveguide, a slot waveguide, and a hybrid SPP waveguide. A long-range hybrid terahertz SPP (LR-HTSPP) is a combination of long-range SPP, and dielectric waveguide modes. It offers the same degree of propagation length as LRSPP and similar mode confinement as HTSPP. In order to better understand and distinguish between SPP and waveguide mode, intensive research has been proposed recently. For example, alternative plasmonic material, such as a graphene-based split-ring structure, has been investigated [17], along with micrometer-level graphene field effect transistors, which have high sensitivity and wide-band tunability throughout the entire THz domain [18]. The development of efficient THz sources and detectors has opened the THz frequency region (i.e., 0.1–10 THz) to numerous applications, including material analysis in microelectronics, non-invasive screening of cancer, label-free biomolecular analysis [16], and optical tweezers [19–22].

In contrast, semiconductor microwire offers applications in nanophotonics, such as waveguides, sensors, photodetectors, and lasers [5–7]. However, the operating wavelength is much longer than the diameter of microwire and yields weak confinement due to a limited index-contrast. This dilemma arises from the difficulty in achieving subwavelengths on an optical scale, when small mode and wire diameters are desirable. To overcome this limitation, we propose using strong terahertz confinement to enhance the optical field strength and the gradient of light field and to determine the optimum size required for potential applications.

An important aspect that needs to be addressed in this work is confining and guiding long wavelength electromagnetic radiation into small-size structures by coupling them with HTSPP, i.e., confining the light and increasing the electromagnetic fields at an interface between two media, of which at least one is conducting [4]. The structure under study outperforms existing hybrid terahertz plasmonic waveguides in terms of the figure of merit (FoM) that allows one to use it in real-life applications, such as optical force in trapping and transporting biomolecules [23] or in high density integrated circuits [1,24]. It is worth mentioning that some works do not cover all aspects of hybrid plasmonic waveguides, such as coupled microwire at THz frequencies.

This paper is organized as follows: A brief theory and structure geometry are addressed in Section 2. In Section 3, numerical results are presented and discussed. Figures of merit are introduced in Section 4, and Section 5 summarizes the results and draws conclusions.

2. Structure geometry

To optimize the trade-off between mode confinement and propagation length in the THz frequency range, a novel structure was adopted [10], as shown in Fig. 1. The structure has the advantage of supporting a long propagation length, which consists of a thin metallic film (silver: Ag) sandwiched between two cylindrical silicon (Si) microwires with a diameter D and a gap distance h. The background material is assumed to be SiO_2. In order to verify the possibility of obtaining a low loss with a long propagation length for HTSPP mode, the complex dielectric function of Ag needs to be considered. The permittivity is described by the well-known Drude model as:

$$\varepsilon_r = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + j\gamma)} \tag{1}$$

where, ε_∞ is the high frequency permittivity, γ is the damping term, and ω_p is the plasma angular frequency [11].

$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon_o m^*}} \tag{2}$$

Here, m^*, e, and n are the electron effective mass, the electron charge, and the carrier density, respectively, and ε_o is the permittivity of free space. The parameters $\omega_p = 1.37 \times 10^{16}$ rad/s and $\gamma = 8.20 \times 10^{13}$ rad/s are taken from [25].

In this paper, the frequency considered is 1 THz, as this is within the critical range of the THz spectrum for spectroscopy, sensing

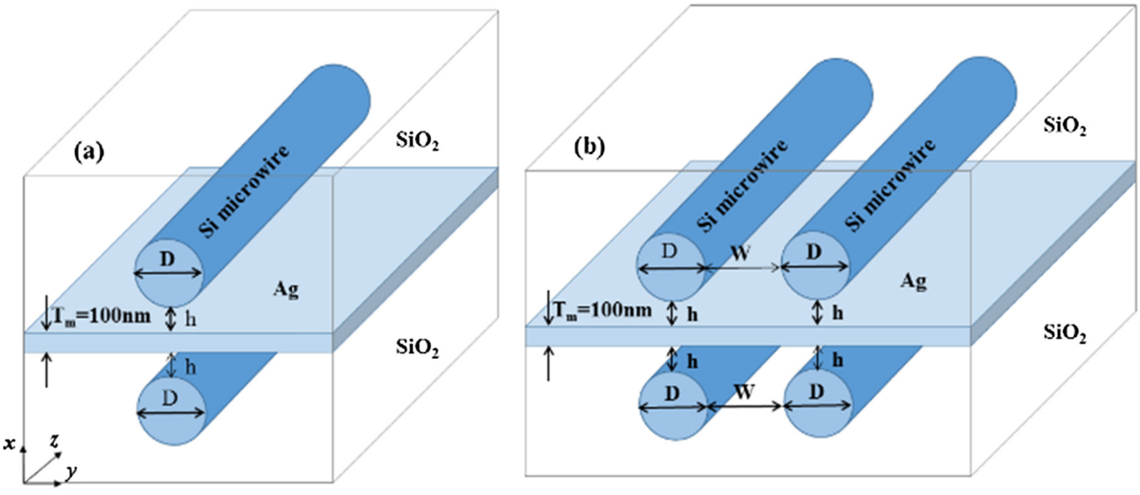

Fig. 1. Schematic diagrams of HPTWG: (a) a single pair of microwires, (b) a double pair of microwires.