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Design, Development and Applications of Spoof Surface Plasmon Transmission Line-Based Sensors at Microwave Frequencies

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Abstract:

At optical frequencies, highly localized surface waves known as surface plasmon polaritons (SPPs) exist at the interface of two mediums with opposing permittivities.Plasmonic metamaterials have been proposed to create subwavelengthstructureson a metal surface in order to create spoof SPPs at microwave or terahertz frequencies.Due to their inheritance of natural SPPs' dispersion characteristics, field confinement, and subwavelength resolution, spoof SPPs are anticipated to providenovel approaches to highly integrated, small, and highly performing advanced circuits and systems.The evolution of spoof SPPs in recent years is covered in this paper, with particular attention paid to the fundamental idea, theory, design process, and microwave engineering applications.The theory and concept of SPPs and spoof SPPs are first presented, followed by the evolution of bulky waveguides to ultrathin transmission lines (TLs) and the special advantages of this novel TL type.The design process is then examined, including the reconfigurable spoof SPPs and the feeding strategy of spoof SPP TLs.It also showcases recent advancements in the engineering realization of plasmonic circuits, including as SPP antennas, active SPP devices, and passive SPP circuits.Lastly, the possible uses and future directions of microwave spoof SPPs are examined.

Introduction:

Dielectric characteristics of different fluid samples are easy to find at microwave frequencies by electromagnetic (EM) field interaction with positive and negative permittivity values in visible and near-infrared wavelengths**.** Pendry et. al. demonstrated first plasmonic metamaterials (structured surface with grooves and holes) which work at low frequencies and consequently other groups also reported the same [1]– [3].

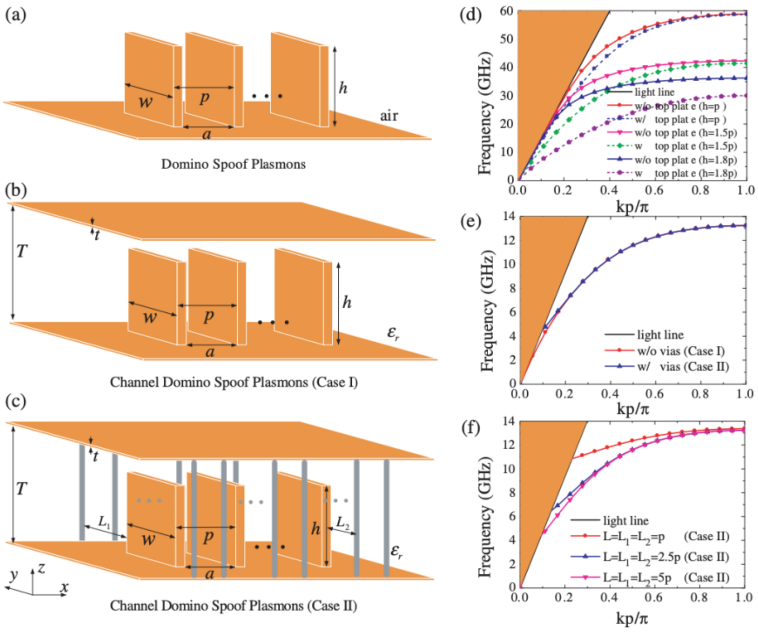

Figure 1. (a) Schematic drawing of the periodical box-shaped domino array etched on a infinite metallic plate to support the traditional DSPs. (b) and (c) Schematic drawing of the channel periodical domino array inside two finite metallic plate without (Case I) or with (Case II) metallic vias,respectively. (d) Dispersion curves of the DSPs and the channel DSPs (Case I) with varying metallic block height h, where p = 1 mm, a = 0.5p, w = 4p, T = 1.9p, t = 0.018p and εr=1. (e) Dispersion curves of the channel DSPs with (Case II) or without (Case I) two-side metallic vias. (f) Dispersion curves of the channel DSPs (Case II) with varying interval L (L = L1 = L2) between the metallic block and the via.

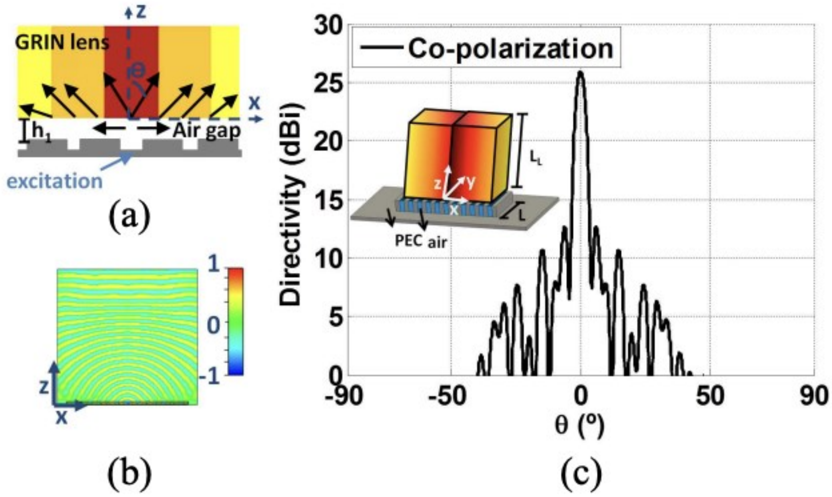

Figure 2. (a) Configuration: waveguide with GRIN lens on the top. (b) Electric field distribution for the combination of waveguide and GRIN lens at 180 GHz. (c) Radiation pattern at φ=0◦ (y=0) plane for the co-polarization of the waveguide with the GRIN lens on the top at 180 GHz.

In the above figure 2, it has been proposed a leaky wave antenna excited in a configuration including various dielectric slabs positioned above a spoof plasmon waveguide. In addition, it has been shown the promising properties of a particular design of this antenna at 180 GHz and whose use for practical THz regime applications is feasible. For this purpose, an additional GRIN lens is proposed, which is able to transform the radiation pattern into broadside, with SLL lower than −15 dB and a cross polarization which is practically negligible.

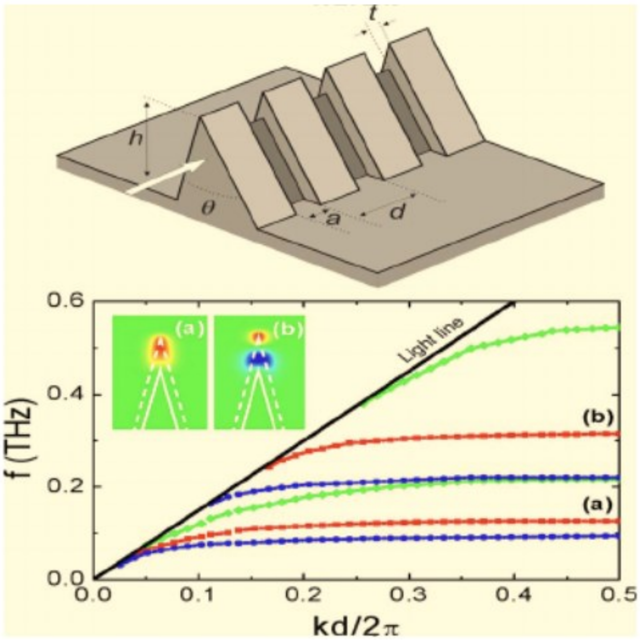

Figure 3 . (Color online) Upper panel, sketch of the proposedwaveguiding scheme. White arrow indicates the directionof propagation. Lower panel, two lowest spoof WPP bands for wedges with threedifferent depths, t: 150m (circles), 100 m (squares), and 50m (diamonds). The rest of thegeometric parameters are described in the text. Insets (a)and (b) show snapshots of the longitudinal component ofthe electric field at the edge of the two bands for the case

In summary, we have shown that corrugated metallic wedges sustain geometrically induced EM guided modes. In the THz regime, these modes are particularly attractive owing to their low loss, excellent transverse confinement, and compatibility with planar technology. We have further demonstrated that by sharpening the wedge angle, lateral focusing of THz waves is achieved.
The Surface Plasmon Polaritons (SSP) do not support at terahertz (THz) and microwave frequencies, due to it act as Perfect Electric Conductors. Several types of recurring patterns have been proposed and studied to transmit the SPP modes. Then artificial SSP's are explored by designing a metal surface with subwavelength patterns like holes and grooves to support microwave and tera hertz (THz) range frequencies. These structures are known as Spoof Surface Plasmon Polaritons (SSPPs), and they attracted a lot of attention. SSPPs have several advantages over the SPPs like tunability, low loss and ease of fabrication [4]–[9].

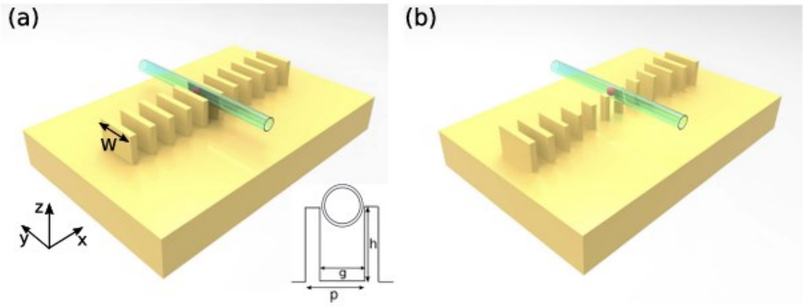

Figure 4. Schematics of the homogeneous (a) and the tapered (b) spoof SPP domino waveguides, with lateral width W, period p, groove depth h, and groove gap width g as indicated in the inset figure. A micro-capillary is positioned in the center groove. The center of the capillary is aligned with the top of the domino blocks.

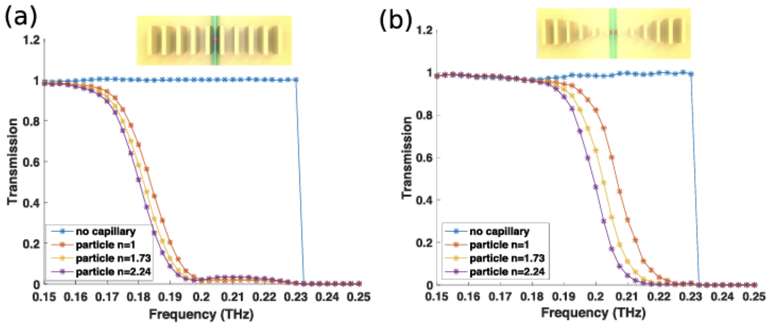

Figure 5. Sensing a single micro-particle passing through the capillary. (a) Transmission spectra of a homogeneous domino waveguide with a single spherical particle in a liquid inside the capillary. The particle, with diameter 90 m, is positioned at the center of the groove, and its refractive index takes values of n = 1, 1.73, 2.24. The background liquid in the capillary n = 1.73. (b) Transmission spectra for the tapered domino waveguide with capillary and particle, with particle parameters being the same as in (a).

The transmission spectrum of the spoof SPP wave is highly sensitive to the refractive index of the analyte, which is on the scale of nanoliters, providing a new method for waveguide-based optofluidic sensing. Furthermore, by exploiting the insensitivity of the spoof SPP on the width of the domino blocks, the tapered domino waveguide with slowly shrinking width can greatly squeeze the spoof SPP mode into a narrower region with better field concentration, making it more promising for the detection of a sub-wavelength micro-particle. We have shown that the high sensitivity is due to the high refractive index liquid or particle decreasing the cut-off frequency of the spoof SPP mode in one groove, resulting in a significant reduction in transmission of the spoof SPP waves through this waveguide section. These findings can be of value for integrated microfluidic THz lab-on-chip devices for biosensing applications such as the analysis of proteins and detection of circulating tumor cells.

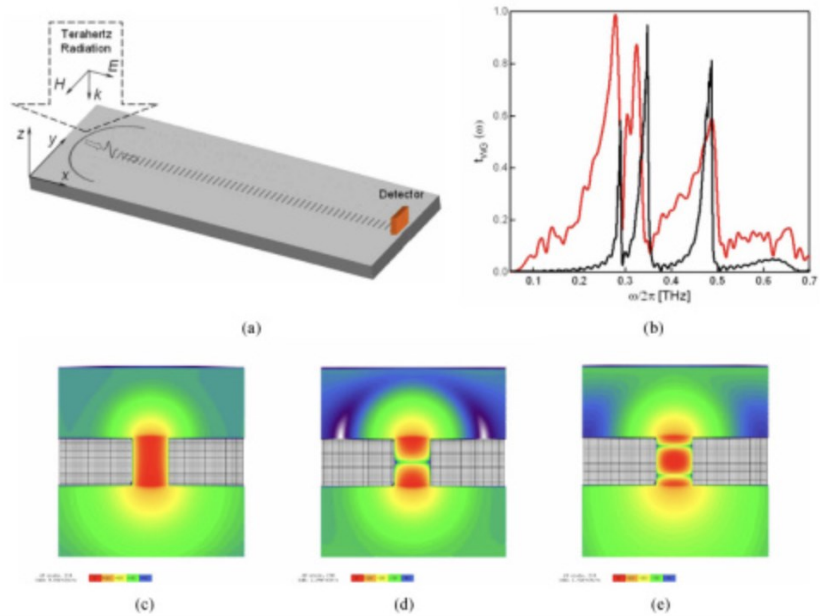

Figure 6. Linear waveguiding properties of the planar plasmonic waveguide fabricated using periodically spaced rectangular apertures. (a) Schematic diagram showing the experimental configuration. A semi-circular groove is used to couple a single-cycle THz pulse to a surface wave pulse, which is subsequently focused at the input of the waveguide. The guided wave is then detected by electro-optic sampling using a (110) ZnTe crystal placed at the output of the waveguide. (b) The guided-wave transmission spectrum, tWG(ω) measured after propagation along the entire waveguide (red trace). The black trace corresponds to the guided-wave transmission spectrum calculated using the FDTD technique. (c)–(e) shows the total electric field distributions in the yz-plane in the rectangular aperture, corresponding to the resonance modes of (c) TM100, (d) TM101 and (e) TM102.

Microwave sensors provide viable solutions for issues in various applications due to their compact size, the capability of non-contact, non-destructive, real-time sensing mechanism and compatibility with other sensing components. The proposed hybrid sensor tests the quality of edible oils and the enhancement in linearity, sensitivity is demonstrated [10]. A planar plasmonic waveguide with SSPP is developed to improve the detection sensitivity and accuracy of the water content in human tissue. Based on water content in human skin tissues, superficial tumors like malignant melanoma can be easily and quickly identified [11]. The quality of food and automotive fluids are analysed using a microwave SPP-like sensor based on substrate integrated waveguide with half-mode (HM SIW). Using low-cost PCB technology, the structure's responses for different toluene/methanol mixtures are tested [12]. To achieve the planar terahertz biosensor N K Tiwari et. al., have developed the complementary split ring resonator

(CSRR) etched on the line's back side of SSPP. With this biosensor by varying the glucose concentration in saline, the patients are diagnosed on hyperglycaemia - hypoglycaemia. Thus, any imbalance in the sodium content may cause abnormal blood pressure inside the little amount of the test solution in microliters [13]. A significant resonance is observed when Ovarian Cancer detectedbysplit ring resonators integrated with spoof SPPs. Resonant frequency shifting makes it possible to clearly discriminate between healthy and malignant ovarian tissues with the help of the improved local electric field [14]. By creating the capacitive slot in the dumbbell shaped groves it behaves like sensing element.Planar spoof sensors with increased sensitivity may be realised with improvedconfinement capabilities[15].

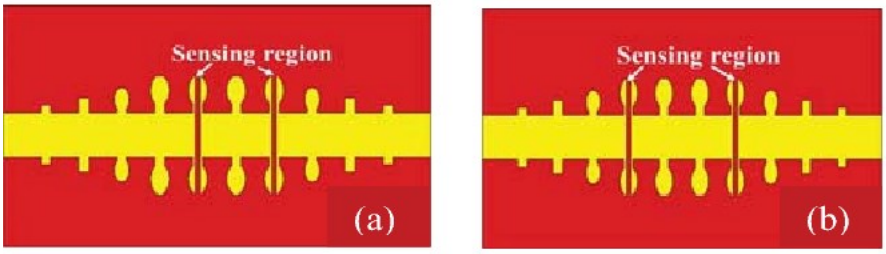

Figure 7. Capacitive loaded Dumbell shaped Sensors

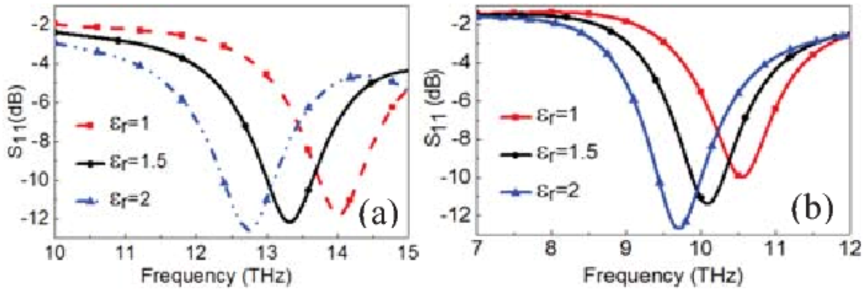

Figure 8. S parameters of the Capacitive loaded Dumbell Shaped Sensors

To design the THz dielectric sensor using the proposed highly confined SSPP transmission an appropriate capacitive slot on the dumbbell cells is created. Design and optimization of the proposed SSPP based resonant structure is performed using the CST-MWS in the THz and microwave frequency range. Thereafter, a prototype of the resonant SSPP (scaled for microwave region) sensor is fabricated, and accordingly the shift in the resonance frequency is measured after loading the sensor with the test specimen.

A compact design with increased sensitivity is proposed with etched CSRRs at the top where electric field found to be maximum [16]. Using a Finite Element Method,designed microfluidic sensor based on a meta-surface absorber, the identification of different edible oil species is proved computationally and experimentally [17]. To achieve greater sensitivity, a gap structure within the waveguide was used in place of a periodic SSPP structure. A tiny layer of immobilised DNS's has significantly changed the waveguide's transmittance, demonstrating the distinction of DNA molecules with various binding states [18]. Researchers established the mathematical solutions to the dispersion relationships of various SSPP modes on the basis of a full-field investigation for the doubly corrugated SSPP (DC-SSPP) waveguiding structure. A scattering matrix approach is used to calculate the transmission characteristics of the sub-wavelength (DC-SSPP) THz structures and the entire dispersion map. It has been demonstrated that such a structure supports the slow-light SSPP mode and unique transmission bands in the frequency domain [19].The extremely contained property of the localised SSP (LSSP) resonator was reported in order to quantify the content of glucose in an aqueous solution. A localised SSP ring resonator, which localises and restricts the EM field, serves as a sensor. As a result, the EM wave makes more contact with the material being tested (SUT), which raises sensitivity [20]. A sensor device for detecting adulteration in fish oil using the dielectric spectroscopy method was implemented in the form of a multi-band microwave patch resonator with an EBG array structure [22].

A circular substrate-integrated waveguide (SIW) sensor with high-Q is developed particularly for chemical and chemical purity sensing applications. An electro-chemical sensor utilizing a metamaterial absorber has been reported. This sensor includes a swastika-shaped copper resonator placed on an FR-4 substrate within the X-band frequency range, to identify various types of chemical liquids based on their electrical properties within the microwave frequency range . Using a single-resonance planar structure, a metamaterial absorber chip for THz biosensing based on SSPPs with THz-TDS is intended to detect viruses. To find the compositions with various dielectric constants, identical virus models are numerically analyzed to evaluate the chip's performance [25]. Microwave sensors are appealing for measuring the conductivity and dielectric properties of biological samples as they offer real-time, label-free and non-invasive detection due to the observation of a rapid change in the response of the detected liquid analyte.

In this work sensor utilizes a spoof surface plasmon polariton (SSPP) waveguide integrated with a triangular unit cell structure to enhance its sensing capabilities. Figure 1 presents a comprehensive visualization of the SSPP waveguide configuration: (a) displays the top view, where the integration of the triangular unit cell can be clearly observed, strategically designed to manipulate the electromagnetic wave propagation. (b) illustrates the bottom view, offering insights into the full symmetry and layout of the copper-based waveguide[26-28]. (c) provides a cross-sectional view, revealing the layer structure and substrate interaction. The waveguide is constructed using a highly conductive copper layer (with an electrical conductivity of 5.8 × 10 7 5.8×10 7 S/m) on both the top and bottom surfaces. This conductive layer is patterned and mounted on an FR-4 substrate, a commonly used material in RF applications, characterized by a relative permittivity of 4.3 and a loss tangent of 0.025. The sensor's physical dimensions are optimized for compactness and performance, with a total length (L) of 200 mm, a width (W) of 20 mm, and a thickness (height) (H) of 1.67 mm. Figure 2 shows the transmission coefficient (S21) as a function of frequency in the GHz range, where the resonance behaviour of the sensor is analysed. The proposed sensor demonstrates an operating frequency at 5.77 GHz, with a sensitivity of 28 MHz, indicating its responsiveness to environmental or material changes[29-30]. Furthermore, it exhibits a high-quality factor (Q-factor) of 44.38, highlighting its capability to distinguish small frequency shifts with minimal energy loss, which is vital for high-precision sensing applications.

Conclusion:

A detailed study of all the literature available is reviewed studied and taken into consideration. The concept and theory of SPPs and spoof SPPs are introduced, along with development from bulky waveguides to ultrathin transmission lines (TLs) and the unique merits of this new type of TL. Then, the design method is studied, including the feeding strategy of spoof SPP TLs and the realization of reconfigurable spoof SPPs. Recent progress on the engineering realization of plasmonic circuits is also demonstrated, including passive SPP circuits, active SPP devices, and SPP antennas. Finally, the future directions and potential applications of microwave spoof SPPs are discussed.

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