Spoof Zenneck waves in terahertz spectral range

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Abstract: We theoretically predict existence of Spoof Zenneck waves in the terahertz spectral range that are supported by corrugated surfaces with subwavelength patterning made of materials with high positive dielectric permittivities.

1. Introduction

The strong spatial confinement of surface waves led to a revolution in sensing. Profiting from small modal sizes of such waves, surface sensing modality offers high sensitivity and precise localization [1, 2]. Particularly, in the visible spectral range, surface plasmon-polaritons propagating at the interface between a metal and an analyte were used to revolutionize the field of biosensing. Recently, THz spectral range (frequencies of 0.1-1 THz) emerged as the next frontier for non-destructive imaging, sensing, and ultra-fast wireless communications [3, 4]. Because of the relative transparency of dry dielectrics to THz radiation and existence of spectral fingerprints for many biological molecules, THz sensing became an emerging research direction that could also benefit from surface wave sensing modality. However, generation and support of highly confined THz modes on flat metal surfaces (analogous to plasmons in the visible) proved to be challenging due to material limitations of metals in the THz spectral range, thus resulting in highly delocalized surface modes. A breakthrough in THz plasmonic came from realization of Spoof Plasmons on corrugated metallic surfaces with subwavelength patterning [5]. In this paper, we propose and theoretically demonstrate the possibility of Spoof Zenneck surface waves that also propagate along a corrugated surface with subwavelength patterning, but in direct opposition to Spoof Plasmons, they require materials with high positive dielectric permittivity. Under certain assumptions such modes can exist even in the case of purely real dielectric permittivities and in the absence of material losses. This work is of particular importance to the THz spectral range, where there is an abundance of ceramics featuring high dielectric permittivity, and practical demonstrations and applications of such modes hold a significant promise.

2. Dispersion relation of Spoof Zenneck waves

Consider a periodic corrugated surface made of material with permittivity ε_m adjacent to a lossless dielectric with permittivity ε_0 as shown in Fig. 1. The periodic structure has a period d and contains grooves of width a and height h.

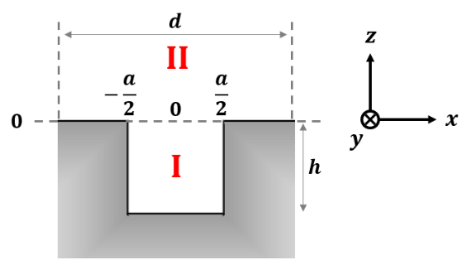

Fig 1. Schematic of the corrugated structure. The period is d and the groove width and depth are a and h. The permittivities of the material and the filling dielectric above the surface and in the grooves are ε_m and ε_0, respectively. The structure is infinite and uniform in the y-direction.

The dispersion relation of Spoof Zenneck waves can be found by solving Maxwell equations in the upper and lower semi-infinite domains, while matching them along $z = 0$, similarly to a standard derivation used for Spoof Plasmons [6]. At the interfaces with material ε_m we use an impedance boundary condition (IBC) [7], which is valid as long as modal field either decays, or suppressed due to destructive interference, or its coherence is destroyed over the propagation distance d-a within the groove walls. Then, for the waves propagating along the grooves (along OZ direction) one can find their propagation constant β_z^I:

$$k_x^I \tan(k_x^I a/2) = -i\frac{k_0\varepsilon_0}{\sqrt{\varepsilon_m}}, \tag{1}$$

where $\beta_z^I = \pm\sqrt{\varepsilon_0 k_0^2 - (k_x^I)^2}$. Then, in the limit of $d \ll \lambda$ (subwavelength corrugation), an analytic expression for the propagation constant β_x^{SZ} of a Spoof Zenneck wave propagating along OX axis can be found by solving Maxwell equations in zone II and then matching the fields, while respecting IBC along $z = 0$:

$$\left(\frac{\varepsilon_0 k_0}{\sqrt{\varepsilon_m}} + k_z^{SZ}\right)\frac{\sin\left(\beta_x^{SZ}\frac{d}{2}\right)}{\sin\left(\beta_x^{SZ}\frac{a}{2}\right)} = \beta_z^I \frac{i\sqrt{\varepsilon_m}\beta_z^I \tan(\beta_z^I h) - \varepsilon_0 k_0}{\sqrt{\varepsilon_m}\beta_z^I - i\varepsilon_0 k_0 \tan(\beta_z^I h)} + \frac{\varepsilon_0 k_0}{\sqrt{\varepsilon_m}}, \qquad (2)$$

where $k_z^{SZ} = \pm\sqrt{\varepsilon_0 k_0^2 - (\beta_x^{SZ})^2}$ is the z-component of the wave vector of the surface wave.

3. Results

Here we present examples of dispersion relations of Spoof Zenneck waves supported by the corrugated surface made of materials with purely real and positive permittivity. To validate our derivations, dispersion relation given by (2) is compared with numerical results obtained using COMSOL. Particularly, solid lines in the left panel of Fig. 2 show dispersion relations (real and imaginary parts) of Spoof Zenneck waves as obtained by solving (1)-(2) using Newton-Raphson iteration method, while dotted lines correspond to COMSOL simulations. The propagation distance $L_x = 1/\mathrm{Im}(\beta_x^{SZ})$ and the penetration depth into air $L_z = 1/|\mathrm{Im}(k_z^{SZ})|$ of the modes are also presented in the right panel. Here we use $d = 50$ µm, $a = 35$ µm and $h = 75$ µm, $\varepsilon_0 = 1$, $\varepsilon_m = 100$ (case of TiO_2 material [8]). From these results, we note that the fundamental modes in Fig. 2 have a superior *cut-off* frequency of 0.95 THz.

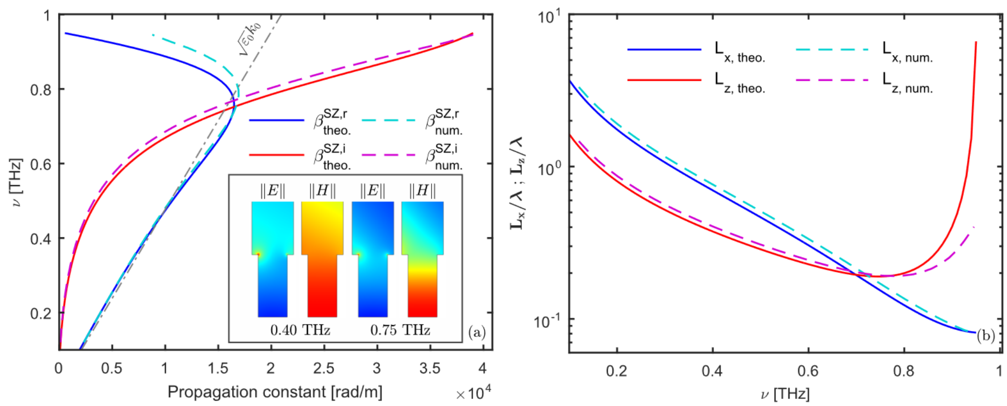

Fig 2. Typical dispersion relations of the spoof Zenneck waves. (a) Real (blue, cyan) and imaginary (reg, magenta) parts of the Spoof Zenneck wave propagation constant as computed by the Newton-Raphson iteration method and (1)-(2) (solid), as well as COMSOL (dotted). (b) Propagation distance (blue, cyan) and penetration depth into air (red, magenta) in units of lambda. (Inserts) Distribution of the electric and magnetic fields above the surface and inside the grooves for 0.40 THz and 0.75 THz.

We see good correspondence between the semi-analytical expressions (1)-(2) and numerical COMSOL simulations in the subwavelength regime $\lambda > 5d$, which covers the operation range of the fundamental modes. In addition, such modes have tight confinement near the interface as the penetration depth into air is mainly subwavelength in the spectral range of interest. Overall, dispersion relation, including the *cut-off* frequencies of Zenneck waves can be easily engineered by changing the value of the period d, the groove width a and the groove height h, which make this kind of metamaterial a great candidate for engineering of THz sensors using highly localized surface modes. This work is also of practical importance as in THz range there are many ceramics that feature high positive permittivities.

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