Investigation of periodic metal structures for terahertz miniature waveguides and resonators

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Abstract

Terahertz (THz) waves, defined as the frequency range of 0.1-10 THz, bridge the gap between microwaves and infrared light. THz waves arouse increasing interest for critical applications in a wide range of fields, such as imaging, sensing, and spectroscopy, due to its unique properties of non-ionization and low photon energy (4.1 *meV* at 1 THz). However, several critical issues hamper THz waves toward practical applications. For example, most THz systems are bulky based on free space optics, which are dependent on the precise alignment and operation. It is thus not easy to handle. Guiding THz wave is also the challenges because of strong water absorption. Therefore, exploring miniature waveguides and resonators in THz optics are urgently requested to improve the wave transportation efficiency. THz waveguides and resonators are normally able to confine electromagnetic waves in the subwavelength regions, and the light-matter interaction is consequently enhanced, beneficial for the optical sensing and waves modulation.

The goal of this thesis is to explore two kinds of periodic metal structures, metal rod arrays (MRAs) and metallic wire woven meshes (MWWMs) to manipulate THz waves individually for the efficient guidance and resonance. In this thesis, THz waveguides and resonators with different geometric parameters are experimentally and numerically investigated in a frequency of 0.1-1 THz

One THz waveguide based on a free-standing metal rod array (MRA) is investigated experimentally and numerically in 0.1-1 THz, including the transverse electric (TE) and transverse magnetic (TM) modes. Compared with available periodical THz structures, the end-coupling configuration of MRA waveguides is advantageous to the integration of dielectric assembly since it does not require couplers for phase matching. One apparent rejection band in the TM mode transmission spectrum, resembling the bandgap of a photonic crystal. The noticeable photonic bandgap is found in the TM transmission spectrum in 0.3–0.4 THz, its spectral width and power distinction can be manipulated by changing the MRA geometry parameters, including the rod diameter, the interspace between adjacent rods, and the propagation length of MRA. This MRA is potential to achieve low loss because of large conductivity of metal at THz frequencies. For an MRA with a period of 0.42 mm, the highest transmission of the guided resonant THz waves is performed at 0.515 THz with strong confinement and a lowest scattering loss of 0.01 cm^{-1}.

Conventional electron beam lithography and direct laser writing are limited in their capabilities to produce waveguides in miniature. Thus, a 3D printer based on digital light processing (DLP) with low-cost and low-time consumption is introduced. The experimental results of 3D printed MRA show a good agreement with simulated results. The MRA waveguide supports two transmission bands, corresponding to the fundamental and high-order transverse magnetic (TM) modes. The fundamental mode behaves a leaky mode, while the high-order TM-mode THz waves are strictly confined inside the MRA structure and are thus sensitive to the metal rod interspace for their spectral positions, bandwidths, transmittances, and attenuation coefficients. Hence asymmetrically assembling metal rods for fine-tuning the interspaces across the optic axis is presented as the critical stratagem to optimize the transportation efficiency of THz waves through an MRA waveguide. By tuning the air interspace between metal rods, the power attenuation and mode confinement can be effectively improved.

Highly confined waveguide modes with the low propagation loss are impossible to work for optical waveguides. Recently, hybrid plasmonic waveguides, integrated by the metal and dielectric waveguides, have

been demonstrated as the solution to achieve the longest waveguide lengths with the highest lateral field confinement. To further reduce the THz propagation loss and simultaneously improve the mode confinement of MRA, a dielectric ribbon is used to integrate a 0.42 mm-Λ MRA to observe its hybrid THz fields and study its possible waveguide applications. Although the spoof plasmonic field effects are not clearly presented in the dispersion curves, the MRA high-order modes can be assumed as the spoof plasmonic field among the metal rods due to the obvious lateral field confinement. Simulated results indicate that the loss and confinement of the MRA based hybrid plasmonic waveguide are efficiently improved by a thin dielectric film. The lowest loss about 0.001 cm^{-1} occurs at the high-frequency transmission band because the high-order mode is tightly confined inside the hybrid waveguide. Besides of the two features, the spectral peak shift of the fundamental mode due to the thickness or refractive index variation of the thin-film integration can also be used for the THz sensing.

Most periodic THz metal structures need a substrate to support, thus an additional absorption is occurred. In order to eliminate the field absorption from the substrate, a substrate-free compact THz resonator consisting of metallic wire woven meshes (MWWM) is proposed and demonstrated. Experimental and numerical results indicated that this metallic wire woven mesh is considered as one kind of THz plasmonic structures with a sharp resonance. The investigation expresses that the spectral-dip with high power-distinction ratio comes from the bending metal wire, referred to as Fano resonances, and the resonance field longitudinally covers the input and output end faces due to the woven wires, thereby having the large field volume for the near-field sensing applications.