Terahertz magnetic and electric Mie resonances of an all-dielectric one-dimensional grating and their sensing capability

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***Abstract*— By using of high-resolution Terahertz time-domain spectroscopy, we show that both the fundamental and higher-order Mie resonances can be excited in both magnetic and electric modes with in the one-dimensional dielectric grating. Furthermore, their highly sensitive capability dependent on the frequency red-shift, line broadening, and transmission decreasing were investigated with increasing refractive index and absorption strength of the surrounding media.**

I. INTRODUCTION

Diffraction of light by periodically one-dimensional (1D) corrugated surface has been a subject of continuing interest since the early days of the electromagnetic theory[1-4]. However, majority of thin metallic-film subwavelength gratings suffer from a high level of radiation losses in metals as well as insertion loss of the high-permittivity or thick substrate, which lead to a low-quality (Q) resonant responses and limit the potential applications as a sensor [5,6].

To avoid energy dissipation in metals as well as insertion loss of thick substrate and present unique resonance properties that were not observed at higher frequencies, the resonant response of an 1D, Silicon (Si)-based grating is designed, fabricated and characterized in the THz regime. Unlike the 1D metallic grating [7], we discovered the high-resolution resonant phenomena in a silicon-based, 1D grating. Also, based on finite-element simulations, the distributions of the electric and magnetic fields at the resonant frequencies are investigated in terms of polarizations and resonant modes. Furthermore, their highly sensitive capability dependent on the frequency red-shift, line broadening, and transmission decreasing were investigated with increasing refractive index and absorption strength of the surrounding media.

II. RESULTS

The 1D dielectric grating used in the experiment was fabricated on a double-side polished Si wafer with a resistivity of 1000 Ω·cm and a dimension of 8 mm × 8 mm × 0.11 mm. The parallel rectangular-shaped silicon rods were cut through the central region of the wafer with dimensions of 5 × 5 mm^2 and realized with a direct-laser-writing (DLW) system by a solid-state nanosecond laser (Enpon-Nano-H532) with a fixed wavelength, pulse duration and out power of 532 nm, 10 ns and 5 W, respectively. The periodic grating lines with a length, period, width, and thickness of 5000, 205, 110 and 110 mm, respectively.

A series of high-qualify Mie resonances were excited in the all-dielectric grating, and displayed strong frequency-selection and polarization-sensitivity behaviors, as indicated in Fig.1(a) and (b). The transmission spectrum of the TE wave shows three transmission minima at 0.644, 0.810 and 1.090 THz, respectively. In particular, the second resonance at 0.810 THz is the predominant sharp dip with a narrower linewidth of 0.08 THz and higher Q-factor of 10.1 comparing to that of the plasmonic Fano resonances in a one-dimensional metallic grating [1,2]. In the case of the TM wave, three transmission dips occur at 0.593, 0.827 and 1.047 THz, respectively.

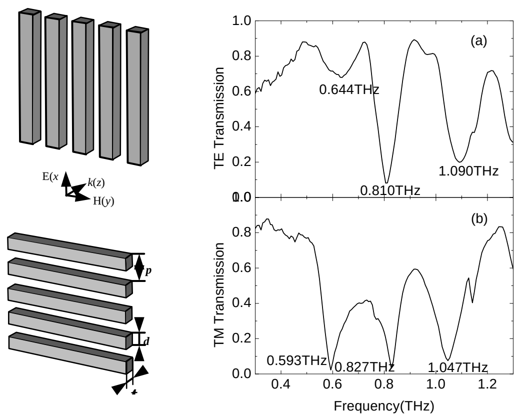

Fig.1. Measured TE (a) and TM (b) transmission for 1D, Si-based grating

Figs. 2 and 3 show the distinct magnetic and electric behaviors at the first three minima of transmission. For the fundamental TE mode, the strong electric field is distributed in the central region of the pillars along ±*x* directions. As same as the conductive current in Ampere's law, it can be equivalent to a straight current wire, as indicated in Figs. 2(a) and (d). For the second TE mode, however, two strong electric fields along +*x* directions build up at the lateral sides of the pillars. Meanwhile, two magnetic loops appear at *y-z* plane, which can be

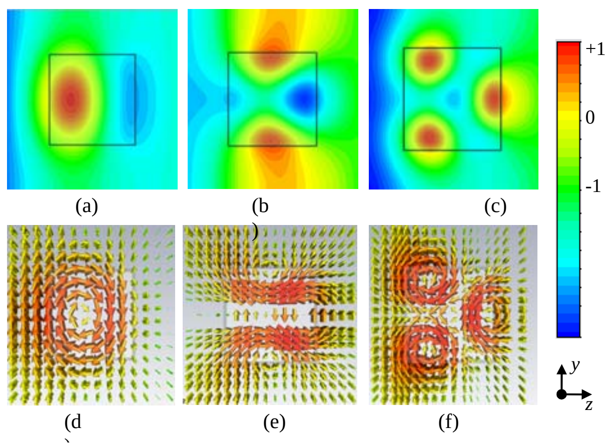

Fig. 2 (color online) Electric field (a, b, c) and magnetic field (d, e, f) maps at the first three minima of TE transmission , respectively.

equivalent to two parallel current wires, as indicated in Figs. 2(b) and (e). Similarly, the magnetic fields reveal three wrapped rings for the third TE mode and the electric fields inside the Si pillars seem to provide a better localization at the extremities or lateral side, which can be equivalent to three parallel current wires, as indicated in Figs. 2 (c) and (f).

In the case of TM mode, the magnetic field is along the grating while the electric field shows typical current loops, as shown in Fig. 3. For the first TM mode, there is a maximum in the magnetic field at the center of the pillar and a corresponding ring-shaped displacement electric field at its cross-section (*x*-*z* plane) is induced by the changing magnetic fields, which are distinct characteristics of magnetic-dipole mode. It is interesting to note that both the second and the third modes have two current loops although their magnetic field distributions along the *y* direction are quite different. The main loops at second mode THz are concentrated in the silicon pillars whereas most of loops at third mode THz disperse in the air. In addition, the tangential component of the electric vectors is continuous whereas the normal component changes abruptly across the surface due to different permittivity.

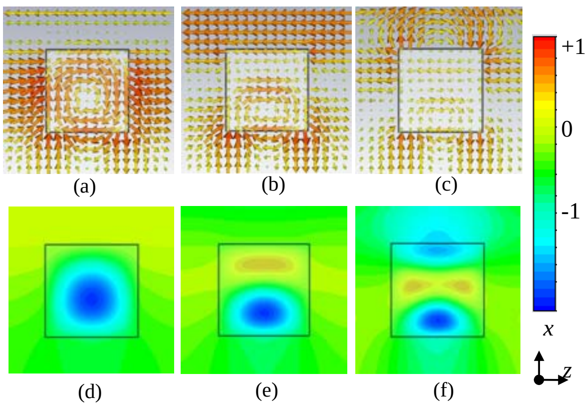

Fig. 3 (color online) Electric field (a, b, c) and magnetic field (d, e, f) maps at the first three minima of TM transmission , respectively.

It is interesting to note that the second TE resonance is a sharp dip with a narrower linewidth and a higher Q-factor. In addition, almost half of electric fields and magnetic loops are concentrated in the silicon pillars whereas the else parts disperse in the background slabs [8]. Therefore, the resonator is sensitive to the dielectric condition of surrounding media. For the application of the resonator as a sensor, all 105-μm thick gaps between the silicon pillars are filled by a liquid dielectric layer with refraction index ranging from 1.0 to 2.0 at σ=0 and 20 S/m. Fig.4 shows that the position, intensity and linewidth of the second TE Mie resonance explicitly dependent on the dielectric condition of surrounding media with the increased redshift in frequency and broadening in linewidth when the refraction index increases. In case of σ=20 S/m, the intensity of the transmission dip is also much sensitive to the change of the refraction index. Our results show that the redshift of central frequency and the intensity of the transmission dipp do not necessarily yield the linear sensitivity. In stead, the linewidth of the resonant dip is an appropriate factor to determine the refractive index of the target media.

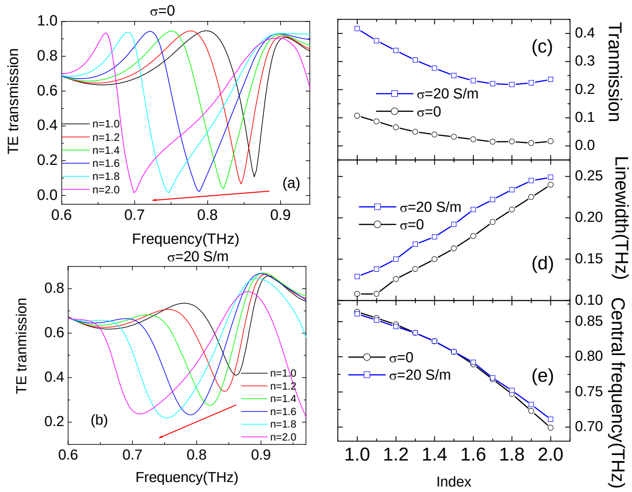

Fig.4. Simulated transmission spectra of the Si-based 1D grating as function of the refractive index when σ=0 (a) and σ=20 S/m (b), and the change of transmission intensity(c), linewidth (d) and central frequency (e) as function of the refractive index n and conductivity σ.

III. Summary

By using high-resolution THz-TDS, we show that both the fundamental and higher-order Mie resonances can be excited in both magnetic and electric modes with in the 1D dielectric grating. Based on the finite element method (FEM) simulation, we achieve an in-depth understanding of the physical mechanisms of the interaction between electro-magnetic fields and such a dielectric grating. In addition, less absorption loss in the dielectric 1D grating is ideal for developing the highly sensitive sensor of liquid dependent on the frequency red-shift, line broadening, and transmission decreasing.

IV. Acknowledges

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