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Dielectric substrate effect on the metamaterial resonances in terahertz frequency range

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ABSTRACT

We report on the effect of dielectric substrate on the resonance shift of metallic metamaterials operating in the terahertz frequency region. The resonance frequencies for various metamaterials obtained by time-domain spectroscopy agree well with calculations based on the finite-difference time-domain method. The dependencies of the resonance frequency to substrate index are studied, and are systematically determined by introducing an effective substrate index. The relative contributions of the substrate index for various metamaterials are obtained by fitting the numerically obtained effective refractive indices as a function of substrate index, which is found to be ~0.63 regardless of the metamaterial geometry.

1. Introduction

Metamaterial devices exhibit fascinating phenomena such as superlensing [1] and invisibility cloakings [2,3] and rely on the successful tailoring of the refractive index of the materials, by fabricating complex subwavelength structures. The functionality of those metamaterials essentially depends on the resonant excitation of the electromagnetic near-field, which is governed by the specific geometrical shape of the conductive materials fabricated on the dielectric substrate. The resonant excitation alters the effective optical properties such as the dielectric constant and magnetic permeabilities in macroscopic point-of-view [4]. In the last few decades, many metamaterials patterns have been introduced and studied intensively, such as the double split-ring resonator [5,6], single split-ring resonator [7,8], electric split-ring resonator [9], and double capacitor [10] operating at the terahertz (THz) or the mid-infrared frequency ranges. They were usually patterned in the conventional metal films; however, more recently nanomaterial network films have been introduced as novel metallic platforms which enable us to manipulate the resonant behaviors by engineering their conductive properties [11,12].

In practice, the resonant frequency of metamaterial is not solely determined by the patterns but also by the refractive index of the supporting substrate [13,14], which alters the effective dimensions of the metamaterials patterns. Considering that one side of the structure is exposed to air, the resonance shall be determined by the combined contribution of substrate index and air index: namely, an effective refractive index n_{eff} [15]. Previous studies on slot antenna arrays—one of the optoelectronic devices with large field confinement—revealed that the substrate contribution is larger than that of the air in n_{eff} by a factor of 2, due to larger confinement of the electromagnetic field at the substrate side. Expanding this approach to the case of metamaterials will provide a convenient tool for the determination of operating frequency, once an appropriate formula can be found to determine the effective refractive index as a function of substrate refractive index for a specific geometry.

In this report, we demonstrate experimentally and numerically that such a formula can be obtained from the linear combination of air and substrate indices for various metamaterial structures operating in the THz frequency region. The resonant peak of various metamaterials patterns, determined by the full-wave simulator MICROWAVE STUDIO by CST Inc. based on the finite-difference time-domain (FDTD) technique, shows good agreement with the experimental data. We obtained the relation between the effective index and the substrate index explicitly for various metamaterials

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patterns from the simulation results, revealing that the substrate contribution is roughly twice as large as that of the air.

2. Sample preparation and experimental methods

Various metamaterial arrays were fabricated in gold metal films (thickness of 100 nm) supported on quartz ($n_{sub} = 1.93$) and silicon ($n_{sub} = 3.38$) substrates by using a conventional photolithography technique. Single split-ring resonator (s-SRR) arrays consist of a rectangle with an outer dimension of 36 × 36 μm^2 with a gap distance $d = 3$ μm (refer to the microscope image in the inset in Fig. 1(a) for details). Similarly, double split-ring resonator (d-SRR) arrays were fabricated with an inner ring dimension of 24 × 24 μm^2, outer ring dimension of 36 × 36 μm^2, and a gap distances of $d = 5$ μm (shown in Fig. 1(b) inset). The electrical ring resonator (e-SRR) arrays were fabricated with a microscale capacitor with a length $l = 10$ μm and a gap distance $d = 3$ μm, which is positioned at the center of the rectangular structure with an outer dimension of 36 × 36 μm^2 (shown in Fig. 1(c) inset). For the above three patterns, the linewidths were kept at 4 μm. Finally, double capacitor (d-CAP) arrays in which two capacitors with $l = 73$ μm and $d = 7$ μm are positioned both top- and bottom-sides. The linewidth of this structure was 6 μm with the outer dimension of 180 × 180 μm^2 (shown in Fig. 1(d) inset).

Resonant transmission of the THz electromagnetic waves through the metamaterial devices has been measured experimentally by using conventional THz time-domain spectroscopy [12]. We used a transverse (TM) polarization configuration throughout the experiment as depicted by a red arrow (in the web version) in the inset of Fig. 1(a). THz transmission spectra for s-SRR, d-SRR, e-SRR, and d-CAP fabricated on Si substrate, are shown as blue curves in Fig. 1(a)–(d), respectively. They were obtained by using a fast Fourier-transform of real time THz transmission amplitudes. Two distinct dips were observed at ∼0.55 THz and ∼1.55 THz in the s-SRR structure, which correspond to the gap mode and dipole mode resonances, respectively [7]. Similarly, the resonances for d-SRR lie at ∼0.4 THz, 0.95 THz, and 1.55 THz, which originate from a gap mode, a dipole mode of the inner ring, and a dipole mode of the outer ring, respectively. In the e-SRR case, a sharp resonance at ∼0.85 THz corresponding to the gap mode was observed together with a broad resonance at ∼2.0 THz associated with the dipole mode [9]. In the d-CAP structure, a single dip corresponding to the gap mode of the capacitor is clearly visible at ∼0.3 THz.

In the case of the quartz substrate (shown by the red curves in Fig. 1), the resonant frequencies change dramatically relative to the Si substrate for all of the metamaterials patterns. For instance, the gap mode resonance in Fig. 1(a) lies at ∼0.8 THz as compared to ∼0.5 THz for the Si substrate, while the dipole mode resonance is not observed in this frequency range. This strong blue-shift is due to the small refractive index of quartz ($n_{quartz} = 1.93$ at 1 THz) as compared to the Si index ($n_{Si} = 3.38$ at 1 THz), which results in shrinkage of the effective dimensions. Similar behaviors of the blue shift have been found in other metamaterials patterns as shown by the red curves in Fig. 1(b)–(d). The resonant peak shift is due to the change in the effective dielectric constant (ε_{eff}) of the capacitor in the metamaterials. The resonance peak f_{res} can be generally expressed by $f_{res} = 1/(2\pi\sqrt{LC})$, where C is the capacitance and L is the inductance [16]. Since C is proportional to ε_{eff}, the resonance frequency is inversely proportional to the effective refractive index n_{eff}. Therefore, the resonance peak position can be obtained for various substrates once we determine the explicit relation between n_{eff} and n_{sub}, as will be shown later.

To predict the electromagnetic behavior of the metamaterials, the structures are simulated by using CST MICROWAVE STUDIO. Fig. 2(a) depicts the near-field distribution of the electric field magnitude at the gap mode resonant frequency for silicon and quartz substrates with TM polarization geometry. In both cases, a significant confinement and enhancement of the electric field is observed in the gap area. However, the magnitude of the field enhancement is considerably larger for the quartz substrate than it is for silicon substrate. This is because the index mismatch between the substrate and the air is larger in the Si case, which usually results in the suppression of the resonant transmission [15]. The transmission spectra have been obtained from the simulation

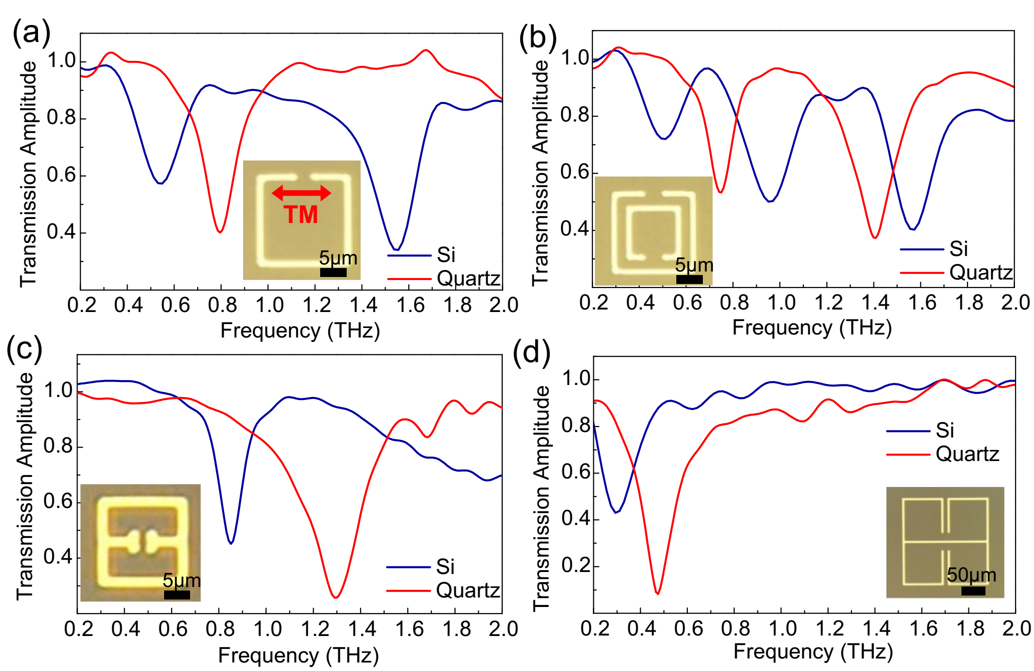

Fig. 1. Experimentally obtained terahertz transmittance of various metamaterial structures of (a) single split-ring resonator, (b) double split-ring resonator, (c) electric split-ring resonator, and (d) double capacitor. Inset figures denote sample geometry.