Substrate Effects on Terahertz Metamaterial Resonances for Various Metal Thicknesses

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We demonstrate dielectric substrate effects on the resonance shift of terahertz metamaterials with various metal thicknesses by using finite-difference time-domain simulations. We found a small red shift in the metamaterial resonance with increasing metal thickness for the free-standing case. Conversely, when the metamaterial pattern was supported by a substrate with a high dielectric constant, the resonant frequency exhibited a large blue shift because the relative contribution of the substrate’s refractive index to the resonant frequency decreased drastically as we increased the metal thickness. We determined the substrate’s refractive index, 1.26, at which the metamaterial resonance was independent of the metal thickness. We extracted the effective refractive index as a function of the substrate’s refractive index explicitly, which was noticeably different for different film thicknesses.

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I. INTRODUCTION

Resonance characteristics of plasmonic metamaterials have attracted great attention lately because they exhibit fascinating electromagnetic responses with potential applications to cloaking [1, 2], superlensing [3], and sensing [4]. The electromagnetic behaviors of metamaterials are determined by the specific geometry of the artificial metal structures fabricated on a dielectric substrate. Many metamaterial patterns have been introduced, such as the double split ring-resonator [5, 6], the single split-ring resonator [7–9], and the electric split-ring resonator [10], operating in the terahertz (THz) or the mid-infrared frequency ranges. On the other hand, the split-ring resonator (SRR) is one of the most commonly used patterns due to its simple geometry. When the SRR structure is excited with a gap-perpendicular electric field, the SRR exhibits an inductive-capacitive resonance (LC resonance) that arises from accumulation of charge at the SRR gap area and the circular current at the side ring of the SRR.

In practice, the resonant frequency of metamaterials is not solely determined by the shape or the dimension of the patterns but also by the refractive index of the surrounding medium, which alters the effective dimensions of the metamaterials patterns [9, 11, 12]. Considering that one side of the structure is exposed to air, the resonance is determined by the combined contributions of the substrate’s refractive index and air’s refractive index: namely, an effective refractive index $n_{eff}$. Recently, we have found that the effective refractive index can be determined as a function of the substrate’s refractive index ($n_{sub}$) and that the substrate’s contribution to the $n_{eff}$ is larger than air’s, due to the larger confinement of the electromagnetic field at the substrate’s side. Previously, we focused on the resonant transmission of the metamaterials fabricated on a thin metallic film of $\sim 100$ nm; however, the metamaterial resonances and, in particular, their relation to the substrate’s refractive index has not been addressed for various metal thicknesses. Our primary concern is whether the relative contribution of the substrate’s refractive index will change as we increase the thickness of the metal films.

In this report, we present finite-difference time-domain (FDTD) simulation results on the resonant frequency of split-ring resonators operating in the THz frequency region for various film thicknesses. We obtained the relation between the effective refractive index and the substrate’s refractive index explicitly, which varies significantly with the metal thickness. In particular, we determined the substrate’s refractive index for which the metamaterial resonance was independent of the metal thickness.

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II. RESULTS AND DISCUSSION

To predict the resonance frequency of metamaterials, the structures were simulated by using Lumerical. A split-ring resonator consists of a rectangle with outer dimensions of $36 \times 36 \, \mu m^2$ with a periodicity of $50 \, \mu m$ and a gap structure with a distance $d = 2 \, \mu m$. The width of the metal strip was $w = 4 \, \mu m$. The SRR pattern was considered to be a perfect electric conductor. The transmission spectra that were obtained through the simulations demonstrated good agreement with the resonant peaks found experimentally in our previous studies [12]. To begin with, we show in Fig. 1(b), the transmission spectra of the SRR pattern without the presence of a substrate (free-standing case) for various metal thicknesses, in a TM polarization geometry. We found a red shift in the resonant frequency as we increased the film thickness ($t_{metal}$) from 100 nm to 20 $\mu m$. In general, the metal thickness is thought to not influence the metamaterial resonance noticeably. Simple analytical modeling of the gap-mode resonance predicts that the resonance is independent of the film thickness because the effects of thickness on the capacitance and the inductance cancel each other [13]. The thickness dependence of the resonance has been addressed for a SRR operating in the visible to near-infrared range [13]. Remarkably, our observation is contrary to those in previous investigations that reported blue-shift in the resonance with increasing thickness. In fact, as we will show below, this discrepancy depends on whether or not the SRR pattern is supported on a dielectric substrate. Therefore, a thickness-dependent metamaterial resonance has to be addressed explicitly, particularly for substrates with different dielectric constants.

In Fig. 2, we show the transmission spectra of SRR patterns with different thicknesses supported on dielectric substrates. Figure 2(a) shows representative results for a quartz substrate with a dielectric constant of $3.73$ ($n_{sub} = 1.93$). Contrary to the results in Fig. 1, a clear blue shift in the resonance is observed as we increase the thickness. Furthermore, the amount of the shift is large compared to that for the free-standing case, reaching as high as 20% for $t_{metal} = 20 \, \mu m$. The resonant frequency is shown as a function of $t_{metal}$ in Fig. 2(b) for both substrate types, quartz and Si ($\varepsilon_{Si} = 11.42$). The resonant frequency increases with increasing $t_{metal}$ in both cases, but the effect is more pronounced in the case of Si with a higher dielectric constant (with the blue-shift of 31% for $t_{metal} = 20 \, \mu m$). The substrate contribution is likely to be very large when the thickness is low; hence, the red-shift in the resonant frequency is large for the higher-dielectric-constant of Si relative to the lower-dielectric-constant of quartz. However, the substrate’s contribution is reduced drastically as $t_{metal}$ increases; therefore, increasing $t_{metal}$ results in relatively larger blue-shifts for the Si case.

More specifically, the resonant peak shift for different dielectric substrates is due to the change in the effective dielectric constant ($\varepsilon_{eff}$) of the capacitor in the metamaterials. The resonance peak $f_{res}$ can be expressed by $f_{res} = 1/(2\pi \sqrt{LC})$, where $C$ is the capacitance and $L$ is the inductance [14]. Because $C$ is proportional to $\varepsilon_{eff}$, the resonance frequency is inversely proportional to the effective refractive index $n_{eff}$. Therefore, the LC resonance peak can be obtained explicitly for various substrates, once we determine the relation between $n_{eff}$ and $n_{sub}$.  

![Fig. 1. (Color online) (a) A schematic of THz transmission through a split-ring resonator with various metal film thicknesses. (b) Simulated THz transmission amplitudes for the freestanding SRR with various $t_{metal}$'s from 100 nm to 20 $\mu m$. (inset) The inset shows SRR pattern used for simulations ($l = 36 \, \mu m$, $d = 2 \, \mu m$, and $w = 4 \, \mu m$) (c) A plot of resonant frequency as a function of $t_{metal}$ for freestanding SRR pattern.](image-url)