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# Tunable Bandwidth of Flexible Far-Infrared Filter using Metamaterial based Split-Ring Resonators

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**Abstract**

**In this paper, we present numerical and experimental studies of bandwidth tunable metamaterials using an overlap distance manipulation. Micro scale split-ring resonator (SRR) arrays were fabricated and characterized on the flexible polyimide films. We confirmed that the stop bandwidth of the fabricated far-infrared (Far-IR) filter can be tunable from 0.85 to 1.95 THz by longitudinal electric couplings between top and bottom SRRs as expected from simulation results.**

## 1. Introduction

Due to their characteristic structures much smaller than the wavelength of light, metamaterials are reported to show unexpectedly enhanced properties from conventional photonic devices [1, 2]. Especially for Far-IR regime, so called the terahertz gap, metamaterials have attracted many research interests to utilize unique properties of terahertz radiation, such as non-destructive detection [3], thermal, and biochemical sensors [4, 5]. In this paper, we proposed a novel metamaterial array filter, consisting of two stacked SRRs with same geometrical parameters, but having different overlap distances between top and bottom cells. By manipulating the overlap distance, the THz band stop filter is designed to be tuned over wide ranges.

## 2. Fabrication

Schematics of fabrication process are shown in Fig. 1(a). The proposed metamaterial array structure consists of flexible substrate (polyimide, 5μm), bottom metal layer (Au/Cr, 200/20nm), spacer (polyimide, 3μm), top metal layer (Au/Cr, 200/20nm), and passivation layer (polyimide, 5μm). The dimensions of the periodic SRRs are designed to have a peek frequency ranging from 1.0THz to 1.6THz, considering the transmission characteristics of the polyimide film which has a high transparency at a frequency range of 0.5-3THz. The details of geometrical parameters are shown in Fig. 1(b). The fabricated array structures are measured by terahertz time-domain spectroscopy (THz-TDS) and compared with numerical simulation results by high frequency structure simulator (HFSS) tools.

## 3. Results and Discussion

The optical properties of the metamaterial arrays are usually discussed in terms of the coupling effects between unit cells by using Lagrangian formalism [6]. In this approach, the bandwidth and resonant frequency are affected by the transverse and longitudinal coupling between adjacent unit cells as described in eq. (1)

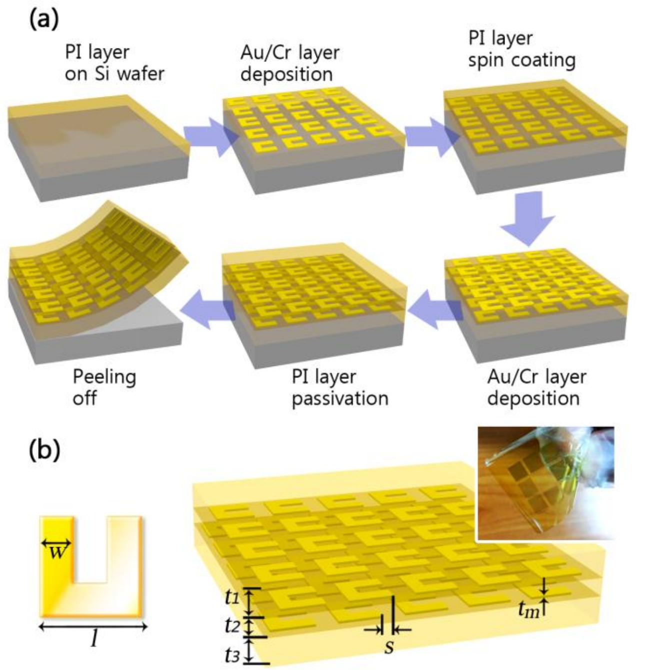


Fig. 1 Structure geometry and fabrication procedures of the proposed array filter. (a) Processing scheme. (b) Schematic diagram of the structure with geometrical parameters: w = 30μm, l = 90μm, $t_1 = t_3 = 5\mu m$, $t_2 = 3\mu m$, $t_m = 220nm$, and s = 0, 15, 30, 45μm. Inset shows a photograph of the fabricated flexible array filter.

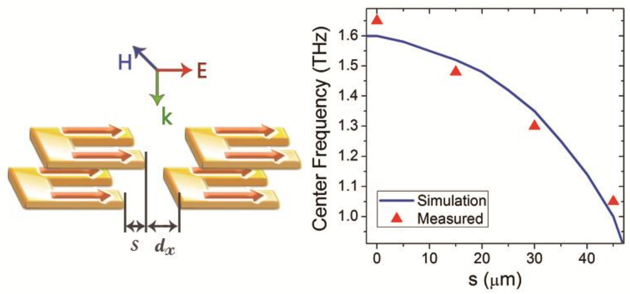


Fig. 2 (Left) Schematics of the alignment of the electric (red arrow) dipoles excited by polarized incident wave. (Right) Simulation and measured results of center frequency as function of the overlap distance (s). $d_x$ is coupling distance between adjacent electric dipoles.

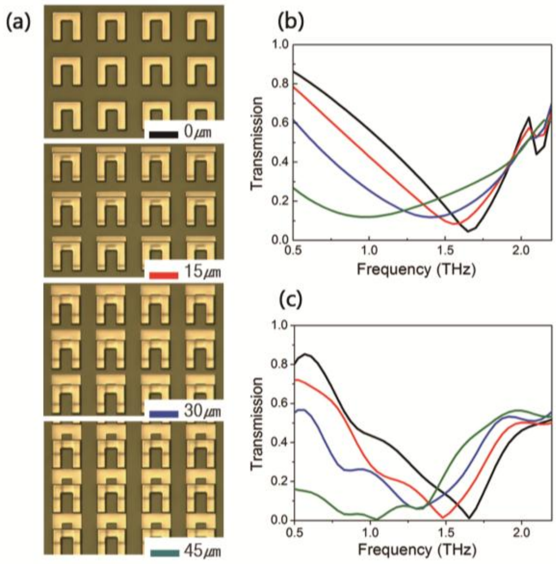


Fig. 3 (a) Optical microscopy images with varying overlap distance between top and bottom THz arrays. (b) Simulation and (c) measured transmission spectra.

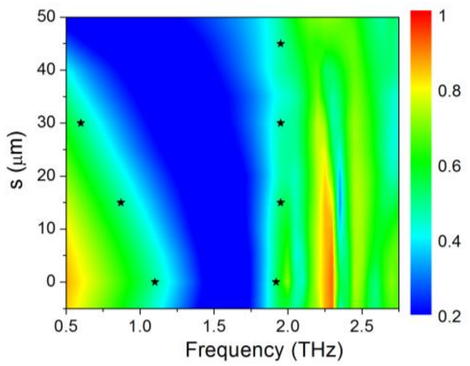


Fig. 4 Broadband transmission with varying overlap distance between top and bottom arrays for electrical excitation. The overlaid stars represent the FWHM of the peak frequency.

$$\omega \propto \omega_0 \sqrt{1 - \frac{4(M_e/L)}{(l+d_x)^3} + \frac{2(M_e/L)}{(l+d_y)^3}} \qquad (1)$$

where $M_e$ is the electric dipole coupling between unit cells and where $\omega_0$ and L are the resonance frequency and inductance of an unit cell, respectively. The coupling coefficient ($M_e$ / L) for the proposed array structure is calculated as $0.12 \times 10^{-12}$ m$^3$.

As shown in Fig. 2, our proposed structures are excited by an incident wave polarized in the x direction. Subsequently, the electric dipoles are formed along legs of SRRs, each dipoles are transversely coupled in y direction and longitudinally coupled in x direction. Fig. 2 shows the center frequency is shifted from 1.6THz to 1.0THz with varying overlap distance **s** between the top and bottom metal layer. We could find that the coupling distance $\mathbf{d_x}$ is reduced due to the shifted top metal layer so that the longitudinal coupling between unit cells increased, resulting in the red shifting of the center frequency. These results indicate that we can tune the center frequency of the filters through relative displacement between top and bottom metal arrays without geometrical scaling.

Optical microscopy images with shifted arrays are shown in Fig. 3(a) and the corresponding simulation and measured transmission spectra are shown in Fig. 3(b) and 3(c), respectively. As overlap distance decreases from 0 to 45μm, the bandwidth broadens and the measured center frequency is red shifted from 1.65THz to 1.04THz. These measured results show a good agreement with simulation results as shown in Fig. 3. Particularly at 2.1THz in Fig. 3(b), the higher order resonance due to the transversely coupled dipole interaction can be observed. These unwanted harmonics can be suppressed by stretching the period of the unit cell [7].

Fig. 4 shows the simulated transmission spectra as function of the overlap distance. The overlaid stars represent the full width at half minimum (FWHM) of the stop-band versus overlap distance. As the overlap distance is increased, the FWHM also increases from 0.85 to 1.95 THz. From the measurement results, we confirmed that a strong coupling between top and bottom cells with decreased coupling distance causes a broadening of the bandwidth as previously discussed. When the overlap distance is larger than 45μm, the proposed array filter nearly rejects all the low frequencies, acting like a high-pass filter. Since the coupling distance becomes nearly zero at the overlap distance of 45μm, thus the array filter is expected to behave as a high-pass filter.

## 4. Conclusions

We demonstrated a flexible Far-IR band-stop filter using stacked single sprit ring resonators. With the proposed metamaterial array filter, we confirmed that the bandwidth and center frequency are tunable by manipulating the overlap distance without scaling any geometric parameter. We expect that our results can provide a basic approach for array filter design and future metamaterial applications.


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