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On-chip Superconducting THz Metamaterial Bandpass Filter

S. Kalhor¹, M. Ghanaatshoar¹, and K. Delfanazari^{2,3,4,*}

¹ Laser and Plasma Research Institute, Shahid Beheshti University, G.C., Evin, 1983969411 Tehran, Iran

² James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

³ Electrical Engineering Division, University of Cambridge, Cambridge CB3 0FA, UK

⁴ Department of Physics, Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK

* kaveh.delfanazari@glasgow.ac.uk

Abstract— We demonstrate a THz bandpass filter (BPF) made from high-temperature (T_c) superconducting $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (BSCCO). The filter offers a thermally tunable dual passband with a flat response in the first passband, a bandwidth of ~ 0.33 THz, and a sharp resonance band-edge transition to the rejection bands of ~ 316 and 96 dB/THz (for left and right edge, respectively), at temperature $T=10$ K far below T_c . As temperature T increases, the sharpness of the band-edge transition to the rejection bands decreases. The proposed BPF can be useful in the realization of a superconducting based THz integrated circuitry.

I. INTRODUCTION

Numerous potential applications of terahertz (THz) range of frequencies highlighted the demand for well-designed components for controlling and manipulating the THz waves. The integrated THz filter is an essential component that can be integrated with THz sources and detectors on the chip scale to realize THz integrated circuitry. Here, a metamaterial band-pass filter (BPF) is presented which is based on the high transition temperature (T_c) superconducting $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (BSCCO). We choose BSCCO superconductor as it is a promising platform for the realization of both coherent THz sources and sensitive detectors [1]–[22]. Our proposed superconducting THz filter device offer a frequency-agile response with temperature. Numerical results show the filter exhibits a dual-band transmission in the targeted THz region.

II. DESIGN METHOD AND RESULTS

Figure 1 shows the unit cell of our proposed electric inductive-capacitive (ELC) resonator metamaterial based on superconducting BSCCO thin film. The superconductor has a thickness of 100 nm and is placed on the sapphire substrate. The polarization of the normal applied THz wave is shown with a yellow arrow in Fig. 1(a).

The metamaterial transmission is shown in Fig. 1(b). The transmission spectra show two resonances which are due to the inductive-capacitive (LC) resonance of each rectangle split ring. Both resonances lose their strength with the temperature. The transmission dip f_1 loses its strength at $T \approx 85$ K (T_c of BSCCO), while f_2 resonance vanishes at about 60 K. Therefore, BPF is in dual-band mode only below $T \approx 60$ K and switches to a single-band pass above $T \approx 60$ K, and up to the T_c of BSCCO. At $T=10$ K far below T_c , the filter has a first band with a flat top, a low S_{21} insertion loss of 0.3 dB, and 0.33 THz 3dB-bandwidth. The out-of-band range is avoided depending on the sharpness of the slope of the resonance. Here, the band-edge

Fig. 1 (a) The schematic diagram of the superconducting bandpass filter's unit cell with structural parameters: $g=2$ μm , $L_1=70$ μm , $L_2=28$ μm , $w=2$ μm and $P=80$ μm , (b) Temperature-dependent THz transmission of BPF at various temperatures, the two pass-bands are shown with grey at $T=10$ K.

transition slope of first band is 316 and 96 THz/dB for right and left edge, respectively. The band-edge transition slope and 3dB-bandwidth decrease as the temperature increases with losing the strength of the resonances.

The BPF resonant tuning is originated from the complex surface impedance $Z_s = R_s + iX_s$ of BSCCO thin film calculated from the temperature-dependent complex conductivity of BSCCO. Here, R_s and X_s are the surface resistance and surface reactance of BSCCO thin film, respectively. In Fig. 2, the surface impedance is shown at $f=0.19$ THz (red) and 0.58 THz (blue), which are the resonance frequencies of transmission spectra at $T=10$ K. The variation of R_s and X_s have a similar trend in both resonance frequencies.

R_s increases with temperature. X_s increases with temperature up to T_c and then decreases.

Fig. 2: The temperature-dependent (a) surface resistance R_s and (b) surface reactance X_s of BSCCO thin film at $f_1=0.19$ THz and $f_2=0.58$ THz.

Damping the resonance strength with temperature is due to the increase of R_s with temperature. Moreover, the lower strength of f_2 originated from larger R_s of BSCCO at f_2 . The surface reactance (X_s) is responsible for shifting the resonance strength. Therefore, a red-shift in resonance frequencies followed by a blue-shift above T_c is expected. No resonance is observed above T_c , which is originated from the large loss. Our results show that BSCCO BPF offers a larger band-edge transition slope and lower insertion loss in comparison to the non-superconducting BPFs [23].

III. CONCLUSION

We have demonstrated a superconducting MM BPFs based on BSCCO ELC resonators with flat bandwidth, a low insertion loss, and a sharp band-edge transition at $T=10$ K. In addition, we have investigated the thermal tuning of BPF characteristics. Our filter is useful for the realization of BSCCO-based complex THz integrated circuitry for many applications.

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