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Kharazmi University

همگام سازی فاز در تشعشع تراهرتز پشته های پیوند جوزفسون ذاتی در ابررسانای Bi2212 با استفاده از بلورهای فوتونی

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چکیده- با هدف افزایش توان خروجی یک زوج منبع تراهرتز مبتنی بر پیوندهای جوزفسون ذاتی پشته شده از ابررسانای دمای بالای Bi2212، عملکرد مولد بررسی شده و با به کار بردن ساختارهای کنترل فاز موج انتشاری و همفاز نمودن امواج خروجی زوج مولد توانسته‌ایم تا به مقدار قابل توجهی افت توان را جبران نمائیم. در این مقاله این امر توسط شبکه‌ای از بلورهای فوتونی با ضریب شکست مؤثر صفر بررسی و با دقت مناسب نشان داده شده است. برای این منظور ابتدا منبع تراهرتز و شبکه‌ی بلور فوتونی مورد نظر را معرفی کرده و مدهای ویژه‌ی بلور فوتونی را با کمک شبیه‌سازی عددی به دست می‌آوریم. سپس به مدل‌سازی موجبری با دو پشته به همراه ساختار جابجاکننده‌ی فاز و همچنین بدون آن می‌پردازیم. نتایج نشان می‌دهند که ایده‌ی مطرح شده، در عمل نیز می‌تواند بسیار کارگشا باشد.

کلید واژه- پیوندهای جوزفسون ذاتی، ابررسانای دمای بالای Bi2212، بلورهای فوتونی با ضریب شکست صفر، منبع تراهرتز.

Phase Synchronization of Generated Terahertz Waves from Stacked Intrinsic Josephson Junctions in Bi2212 Superconductors Utilizing Photonic Crystals

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Abstract- Power enhancement of generated terahertz waves from a pair of stacked Intrinsic Josephson Junctions (IJJ) in high-temperature superconductor, Bi2212, is investigated. We successfully could compensate the power attenuation with phase manipulating structures of propagating waves, synchronizing the phase of sources. In this paper, using zero-refractive index photonic crystals for this purpose is analyzed and demonstrated with high precision. After introducing Bi2212 terahertz emitters, and zero-refractive index photonic crystals, we numerically compute proposed zero-refractive index photonic crystal modes. Furthermore, we model a waveguide with two sources with and without the phase shifting structure. Results show that this idea could be promising for applied purposes.

Keywords: Intrinsic Josephson Junctions, High-Temperature Superconductors, Zero-Refractive Index Photonic Crystals, Terahertz Source

1. Introduction

For terahertz (THz) applications we need compact and tunable sources, which has simple fabrication processes also with high output emitted power. One of the promising materials is high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212). This material is a ceramic consisting of Intrinsic Josephson Junctions (IJJs). These IJJs can be used as a THz emitter due to Josephson AC effect. For the first time THz radiation was observed from a Bi2212 mesa structure in cryogenic temperature with efforts of Ozyuzer et. al in 2007 [1].

As reported in previous works [1-4] we can assume that a single stack which consists of several IJJs with high accuracy have coherent emission, meaning that we can assume a single stack as an independent THz emitter with specified characters such as amplitude, frequency, and initial spatial phase. Various methods had been presented [1-4] to synchronize IJJs in a single stack to increase output emitted power such as thermal management of internal hot spots in the IJJs [2], modulating bias current [4], applying external magnetic field [1-4], etc.

A typical way to increase the output power of the electromagnetic wave (EMW) source system is arranging the stacks properly as an array. Regardless of syncing IJJs in each Bi2212 stack, assuming coherent emission for each Bi2212 stack, this array that may consists of several stacks of IJJs also need to be synchronized. Although it is better to synchronize IJJs internally, but in the case of two spatially separated stacks it is extremely hard.

In this paper, we synchronize THz radiated waves from an array consists of two series stacks of IJJs based on Bi2212 using photonic crystals (PCs). At first, we introduce a PC-based THz phase shifter. In the next section, we model a waveguide consisting two stacks as two periodic input ports with some phase difference and numerically compute Maxwell's equations to obtain total emitted electromagnetic waves and total power flow in the peripheral environment using Finite-Element-Method (FEM). Finally, we repeat this procedure with an additional PC-based THz phase shifter and show that the power flow has grown up significantly.

2. THz PC-based Phase Shifter

As we reported in [5], Zero-Refractive Index Metamaterials (ZRIMs) can be built with Photonic Crystals (PCs) and hence THz phase shifters can be built with concept of ZRIMs. As shown in [۶], a square photonic crystal (Si rods in the air) embedded in a waveguide with PMC sidewalls can be used as a phase shifter for THz waves with TE polarization. In fact, as shown earlier [6], these embedded PCs can pass THz EMWs without any loss and phase changes. A single PC-based ZRIM structure can be helpful for us here. Since these structures ideally have zero phase accumulation (zero phase delay), the input and output waves are in same phase. The phase is saved in input and is handed over in output at one point ahead. Therefore, one can synchronize two EMWs with different spatial phases emitted from two different ports [6].

2.1. PC ZRIM Unit Cell

Unit cell of a PC-based ZRIM structure is shown in Figure 1. This unit cell with constitutive parameters of a=150μm, r=30μm and silicon rods in the air exhibits zero refractive index. In fact, when we use Effective Medium Theory (EMT) along with Mie Scattering Theory for a two dimensional (2D) dielectric cylinder stands alone in the air, we get effective refractive index as zero [7].

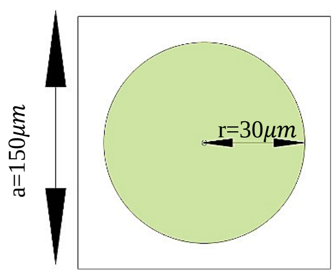

Figure 1. Unit cell of PC ZRIM. Si rod in the air.

We numerically computed effective refractive index using mode solver around the 1082 GHz (Dirac-point frequency. See [5,8]) and presented them in Figure 2. As shown in this figure, for first three modes real part of n_{eff} is zero, and n_{eff} just have a small imaginary part (mode number two and three have opposite signs). Mode number four approximately have $n_{eff} = 0$. In mode five we get almost 1 for real part and as we can see all the E_z profile is confined inside the Si rod and outside it electric field is zero. Considering simulation process accuracy we generally obtain effective refractive index of zero in all these five modes.

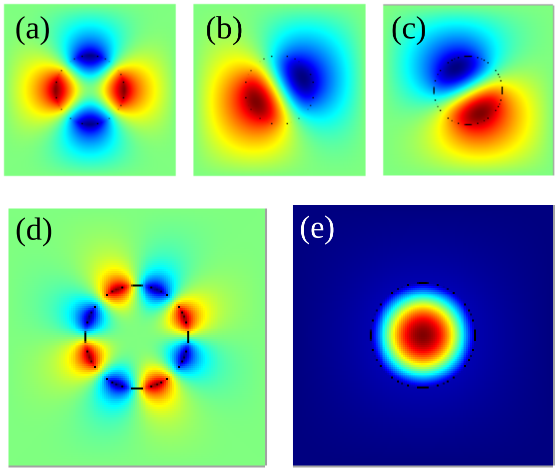

Figure 2. Electric field profile for **(a)** $n_{eff} \cong -i \times 0.80438$, **(b)** $n_{eff} \cong -i \times 0.18509$, **(c)** $n_{eff} \cong +i \times 0.18509$, **(d)** $n_{eff} \cong (0.04276) + i \times 3.3490 \times 10^{-15}$, and **(e)** $n_{eff} \cong (0.98140) + i \times 9.5556 \times 10^{-13}$ in the unit cell.

3. Two Series Stacks of Bi2212

3.1. Radiation of Two Stacks with **59**°spatial phase difference

Arrangement of two stacks is shown in Figure 3. In this figure two stacks with internal layers and up-down Au electrodes are shown. IJJs (CuO_2-$Bi_2Sr_2O_4$-CuO_2) are interval layers. In our simulations we modelled this arrangement as two series periodic ports with 59° phase difference in two-dimensional (2D) space (as shown in Figure 4a, 5a). It is noted that this phase difference is selected with respect to ZRIM structure ability to phase compensation. In fact, in order to obtain exact phase difference between these stacks we should consider the many phenomena that exist in superconductivity [1-4]. Since this procedure is too large we have neglected it and assumed an arbitrary phase difference between two stacks. On the other hand, as we reported in [5], we could get 11° phase shift using a ZRIM structure with 13 columns of Si rods which is closer to reality of IJJs, but 59° phase shift corresponding to 4 columns of Si rods have much easier way to simulate.

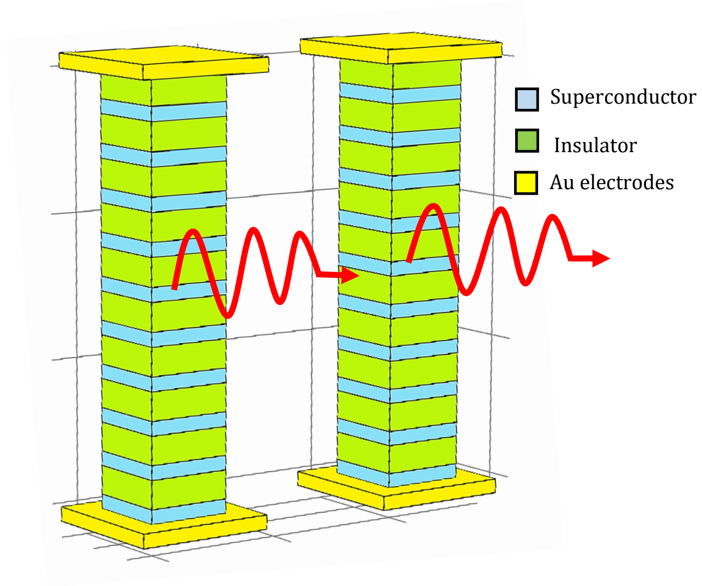

Figure 3. Two stacked IJJs.

In our system we used Perfectly-Matched-Layer (PML) side domains in order to modelling perfect absorption.

3.2. Enhanced Radiation of Two Stacks with **59**°spatial phase difference

As shown in Figure 5, we put ZRIM structure with 4×2 lattice of Si rods ($\varepsilon = 12.5$) in front of Port.1 with initial phase of 59°. As we can see, in addition to enhanced power flow in free space this phase shifter enhanced directivity of THz radiation (in comparison to Figure 4). Two small side layers of ZRIM structure are PMC boundary conditions, as reported in [6]. For simplicity, we use Scattering Boundary Conditions (SBC) in the input side of the system instead of PML.

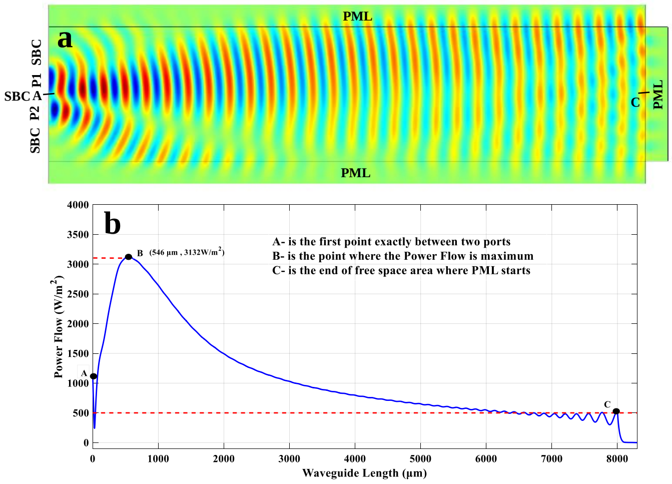

Figure 4. (a) Simulated electric field for two periodic port with phase difference of 59° in free space with PML side domains. **(b)** Electromagnetic power flow in considered region.

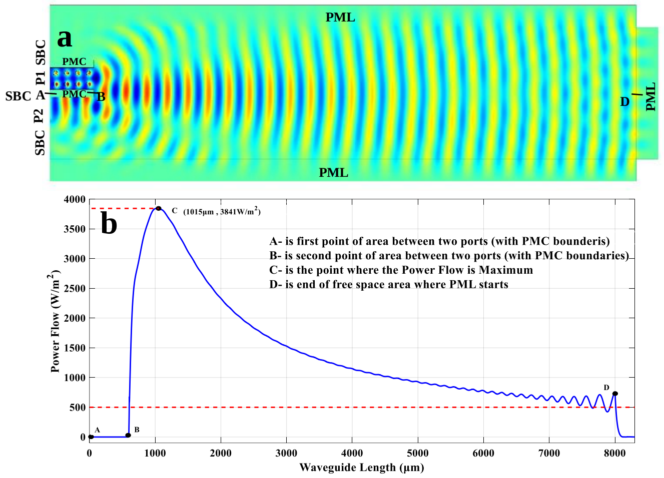

Figure 5. (a) Same as Figure 3(a) but with ZRIM and PMC layers. **(b)** Enhanced electromagnetic power flow.

Conclusion

An idea based on PC ZRIMs is proposed for power enhancement of an array of two Bi2212 stacked THz emitters. PC ZRIM structural properties are set to make a Dirac-point at 1.082 THz. In the first step we numerically computed eigenmodes of the ZRIM. We have applied a reasonable phase difference between two Bi2212 stacks, which was extracted from ZRIM ability to phase compensation. Afterwards, we modelled two Bi2212 stacks as two periodic input ports with desired phase difference. Electric field profiles and power flows for both cases (with and without ZRIM) were plotted in order to analyse proposed idea. This idea can be used in addition to other various internal synchronization methods for more enhancement.

References

[1] K. Kadowaki, H. Yamaguchi, K. Kawamata, T. Yamamoto, H. Minami, I. Kakeya, U. Welp, L.Ozyuzer, A. Koshelev, C. Kurter, K. E. Gray, and W. –k. Kwok, "Direct observation of terahertz electromagnetic waves emitted from intrinsic Josephson junctions in single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$," Physica C, 468, 634-639, 2008.

[2] T. Kashiwagi, T. Yamamoto, H. Minami, M. Tsujimoto, R. Yoshizaki, K. Delfanazari, T. Kitamura, C. Watanabe, K. Nakade, T. Yasui, K. Asanuma, Y. Saiwai, Y. Shibano, T. Enomoto, H. Kubo, K. Sakamoto, T. Katsuragawa, B. Markovic, J. Mirkovic, R. A. Klemm, and K. Kadowaki, "Efficient Fabrication of Intrinsic-Josephson-Junction Terahertz Oscillators with Greatly Reduced Self-Heating Effects," Phys. Rev. Apl. Vol. 4, 2015.

[3] H. Zandi, A. Kokabi, A. A. Jafarpour, S. Khorasani, M. Fardmanesh, and A. Adibi, "Photonic band structure of isotropic and anisotropic Abrikosov lattices in superconductor," Physica C, Vol. 467, pp. 51, Dec. 2007.

[4] A. Kokabi, H. Kamrani, and M. Fardmanesh, "Terahertz Radiation Power Characterization and Optimization of Stack of Intrinsic Josephson Junctions," accepted for publication in IEEE Trans. On App. Supercond, 2012.

[5] A. H. Ghaffari, and H. Zandi, "Total Phase Shift of Terahertz Wave in a Rectangular Waveguide with Zero-Refractive Index Metamaterial," Journal of Physics Communications, IOP science, 2019.

[6] X. Zhao, X. Zhang, P. Cao, L. Cheng, Q. Shao, W. Kong, and L. Gong, "Tunable phase shifter with zero refractive index photonic crystal," Optik, Vol. 124, pp. 2751-2753, 2013.

[7] Y. Wu, J. Li, Z. Q. Zhang, and C. T. Chan, "Effective medium theory for magnetodielectric composites: Beyond the long-wavelength limit," Physical Review B, vol. 74, 085111, 2006.

[8] M. H. Aram, and S. Khorasani, "Dirac-Point in Photonic Crystal Slab" Optics and Photonics Society of Iran, Vol. 21, pp. 1153-1156, 2014. محمد حسن آرام و سینا خراسانی "نقطه ی دیراک در تیغه های بلور فوتونی"، بیست و یکمین کنفرانس اپتیک و فوتونیک ایران و هفتمین کنفرانس مهندسی و فناوری فوتونیک ایران، دانشگاه شهید بهشتی، ۱۳۹۳