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The study of thermal tunable coupling between a Superconducting photonic crystal waveguide and semi-circular photonic crystal

Somayeh Oskooi, Jamal Barvestani*

Department of Solid State Physics, Faculty of Physics, University of Tabriz, Tabriz, Iran

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ABSTRACT

Through the present study, we investigated the light coupling between superconducting photonic crystal waveguide and a semi-circular photonic crystal. By using the finite difference time domain method, we evaluated the coupling efficiency between the mentioned structures at the various temperatures for different waveguide sizes. Calculation demonstrated that the coupling efficiency strongly depended on the temperature of the superconductor. The peak value of the coupling efficiency was influenced by the size of the nearest neighbor rods of waveguide. The results have shown that it is possible to obtain high efficiency at the desired temperature with proper selection of physical parameters in far-infrared frequency region. This structure has great potential in the optical integration and other areas.

1. Introduction

Photonic crystals (PhCs) are the artificial dielectric materials with periodic modulation of the refractive index where propagation of the electromagnetic waves along the direction of the periodicity are restricted to a few spectra [1,2]. By introducing the various defects into the PhCs, different localized defect modes will appear within the photonic band gap (PBG); and therefore, diverse promising tools for controlling the flow of electromagnetic waves in the integrated optical devices can be considered [3–7]. For example, the photonic crystal waveguide (PCW) is created by removing one or several rows of the atoms of PhC, which guides the light over sharp bends by strong confining of the propagating modes with the help of the Bragg reflection mechanisms.

It is necessary to mention that from the technical point of view, coupling the light between conventional waveguide and PCW is still a challenge because of mismatch mode widths. To solve this failure, many structures such as tapered waveguide junctions [8], adiabatic tapers [9], graded index photonic crystal, in which vary the parameters gradually as the refractive index [10], radius [11], and lattice constant [12] have been proposed. Recently, Wang et al. presented a new structure, including a PCW and half of a two-dimensional (2D) circular PhC, to realize the optical coupling [13]. They calculated the equi-frequency contours to obtain a proper frequency which has been designed to convert a wide incident beam into spot. Following the mentioned work, we chose a similar structure and employed their optimized frequency to examine the coupling efficiency, with this main difference, that the waveguide rod was replaced with superconducting material. Once the PhC has been fabricated, its optical properties are immutable and remain unaltered. Therefore, employing the tunable elements in the PhCs give us the possibility to tune the optical properties with considerable flexibility, which leads to the novel applications such as optical shutters and superconducting elements that have low loss benefit [14–18]. Permittivity of the superconductor can be modified by external magnetic fields and the temperature.

The present article investigated the tunability of the coupling efficiency between semi-circular photonic crystal (SeCPC) and superconducting PCW versus the temperature of the superconductor which was composed of copper oxide high temperature superconductor ($Bi_{1.85}Pb_{0.35}Sr_2Ca_2Cu_{3.1}O_y$) for various values of the waveguide radii. In addition, the effect of the first and the second adjacent rows radii were analyzed and explored on the coupling efficiency. The frequency range has been employed in far-infrared region, with a frequency of about 408 GHz. Two numerical methods were used for obtaining results. The plane wave expansion method, which had been used to find the waveguide modes and the finite difference time domain (FDTD) method that was utilized to evaluate the coupling efficiency. The format of the current paper is organized as follows: in Section 2, the coupler structure is given to be used through the calculations. Section 3 is included the analytical results and discussions for tunable coupling efficiency. Finally, Section 4 is concluded by brief comments.

2. Coupler structure and characterization

As it was mentioned before and according to Ref. [13], the proposed structure is composed of semi-circular photonic crystal

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* Corresponding author. Fax: +98 4133341244.
E-mail address: barvestani@tabrizu.ac.ir (J. Barvestani).

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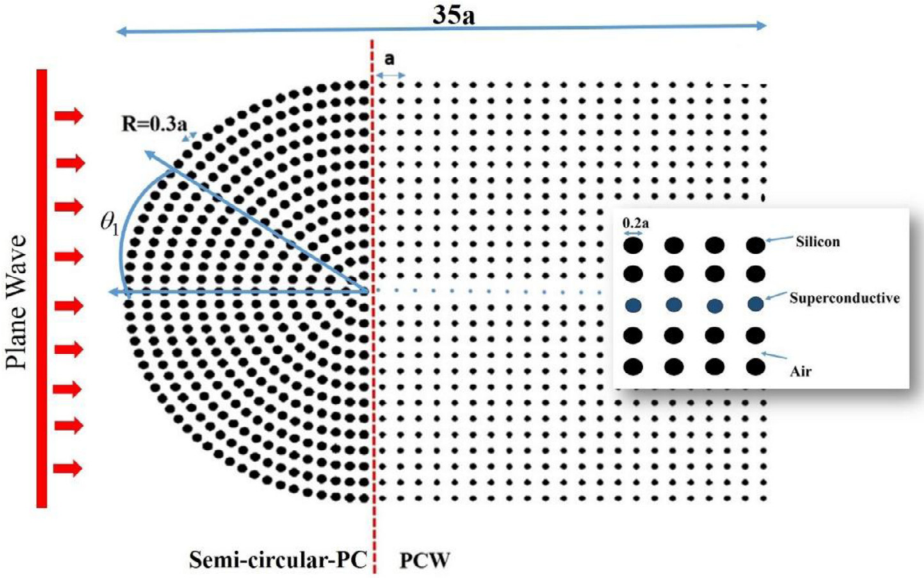

Fig. 1. Schematic representation of our used structure. This structure includes SeCPC (left) and PCW (right side) which are composed of silicon rods with the radius of 0.3a and 0.2a, respectively. Superconducting PCW can be constructed by replacing one row of rods by superconductor one, as depicted in the inset. The vertical dashed red line denotes the boundary of these structures. The plane wave is incident from the left of the structure. The dielectric constant of Silicon rods is assumed to be 11.56, in our calculations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article

and a photonic crystal waveguide, as depicted in Fig. 1. As it is schematically shown in Fig. 1, a plane wave which spreads from left of SeCPC will be focused on the right of SeCPC in the specific frequency range (0.290–0.390 a/λ) [13]. Either of these structures consists of silicon or superconductor rods with air spacing between them in two-dimensional array with infinite height. The SeCPC structure is composed of several concentric semi-circles which are made of dielectric cylinders with single cylinder in the center. The positions of the dielectric cylinders in the X–Y plane for such a SeCPC are given by Rn+1− Rn= a, Θn= π /(4 ×n), where Rn is the radii of the Nth concentric circle, a is the lattice constant, Θn is the angle between adjacent dielectric cylinders in the Nth concentric circle, R1=a, and Θ1=π/4. The radius of dielectric cylinders is 0.3a. In our calculations, the dielectric constant of the rods equals to 11.56 which corresponds to silicon (In our selected spectral region and temperatures the refractive index of Si is approximately constant [19]) and we deal with infinite height rods. However, for finite height PhC, (PhC slab) modal properties of PhC can be changed. For example, for rod slab photonic crystal below 2.25a height the extended and gap region sharply changes. Then, our results approximately are the case above this critical height [see chapter 8 of ref. [1]]. The PCW is composed of silicon rods in squared lattice in which one row of dielectric rods is replaced by $Bi_{1.85}Pb_{0.35}Sr_2Ca_2Cu_{3.1}O_y$, superconductor rods with critical temperature 107 K and zero-temperature c-axis London penetration depth $\lambda_L(5K) = 23\mu\text{m}$ (this copper oxide high temperature superconductor show the superconductivity under liquid nitrogen) [14,15]. The rods' radii of the PCW are 0.2a (Table 1) .

Table 1
Our used parameters in calculations.

Parameter	Value
Constant lattice	$a = 250\mu\text{m}$[14]
Radius of Semi-Circular-PC	$R = 0.3 * a$
Radius of PCW	$R = 0.2^* a$
zero-temperature London penetration depth	$\lambda_L(5K) = 23\mu\text{m}$[14]
critical temperature	$T_c = 107^\circ$ K[14]
	$p = 1$[14]
high frequency permittivity of superconductor	$\varepsilon_{sc} = 12$[14]
dielectric constant of air	$\varepsilon_{air} = 1$
dielectric constant of silicon	$\varepsilon_{si} = 11.56$[13]
Normalized frequency	$W = 0.34$[13]

3. Numerical results and analysis

In this section, we present the calculated results for the coupling efficiency between a superconducting photonic crystal and half of a 2D circular PhC for the TM mode (by assuming that the electric field of electromagnetic waves is parallel to the z-axis i.e. rods). Superconducting rods are assumed to be parallel to the c axis in copper oxide HTSCs [14]. The wave equation of the electric field can be written as below [1]:

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E}(\vec{r}) = \left(\frac{\omega}{c}\right)^2 \varepsilon(\omega)\vec{E}(\vec{r}), \tag{1}$$

Where ω and c are the frequency of the external electric wave and speed of light, respectively. The dielectric constant ε(ω) is constant for all rods except for $Bi_{1.85}Pb_{0.35}Sr_2Ca_2Cu_{3.1}O_y$, superconductor in which by using the two-fluid model at nonzero temperatures can be written as:

$$\varepsilon(\omega) = \varepsilon_{SC}\left[1 - \frac{\omega_{sp}^2}{\omega^2} - \frac{\omega_{np}^2}{\omega(\omega + i\gamma)}\right]. \tag{2}$$

Here, ε_{sc} is high frequency permittivity of superconductor which equals 12 (see ref. [14]), ω_{sp} is the plasma frequency of the superconducting.

$$\omega_{sp} = c/\lambda_L(T)\sqrt{\varepsilon_{sc}}. \tag{3}$$

$\lambda_L(T)$ is defined as the London penetration depth in which its dependency on the temperature was accessed from the Gorter–Casimir result and is expressed as below:

$$\lambda_L(T) = \lambda_L(0)/\sqrt{1 - T/T_c}, \tag{4}$$

where T_c and $\lambda_L(0)$ are the transition temperature of the superconductor and zero-temperature London penetration depth, respectively. In our desired frequency, the last term $\frac{\omega_{np}^2}{\omega(\omega+i\gamma)}$, does not