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

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A B S T R A C T

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.

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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 gives 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 (SePC) and superconducting PCW versus the temperature of the superconductor which was composed of copper oxide high temperature superconductor (\(\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}\)) 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
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 infinite 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 Bi1.185Pb0.35Sr2Ca2Cu3Oy, superconductor rods with critical temperature 107 K and zero-temperature c-axis London penetration depth λc(5K) = 23μm (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).

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]:

\[ \nabla \times \nabla \times \vec{E}(r) = \left( \frac{\omega}{c} \right)^2 \varepsilon(\omega)\vec{E}(r). \]  

(1)

Where ω and c are the frequency of the external electric wave and speed of light, respectively. The dielectric constant \( \varepsilon(\omega) \) is constant for all rods except for \( Bi_{1.185}Pb_{0.35}Sr_{2}Ca_{2}Cu_{3}Oy \), superconductor in which by using the two-fluid model at nonzero temperatures can be written as:

\[ \varepsilon(\omega) = \varepsilon_{\infty} \left[ 1 - \frac{\omega_{op}^2}{\omega^2} - \frac{\omega_{pp}^2}{\omega^2(\omega + i\gamma)} \right], \]  

(2)

Here, \( \varepsilon_{\infty} \) is high frequency permittivity of superconductor which equals 12 (see ref. [14]), \( \omega_{op} \) is the plasma frequency of the superconducting.

\[ \omega_{pp} = c/\lambda_{L}(T)\sqrt{\varepsilon_{\infty}}. \]  

(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:

\[ \lambda_{L}(T) = \lambda_{L}(0)/\sqrt{1-T/T_{c}}. \]  

(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 \( \frac{\omega_{pp}^2}{\omega^2(\omega + i\gamma)} \) does not

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affect \( \varepsilon(\omega) \) much. Therefore, the term on the right side of Eq. (2), and \( \varepsilon(\omega) \) were neglected then became a simple Drude model. First of all, the results of the modal properties of superconducting PCW were presented by employing the plane wave expansion method by using self written code. By defining the \( \eta(\vec{r}) = \frac{1}{\tau_0(\vec{r})} \) and \( \xi(\vec{r}) = \frac{\omega^2}{c^2} \), expanding \( \eta(\vec{r}) \) and \( \xi(\vec{r}) \) by Fourier series and applying the Bloch theorem to \( E(\vec{r}) \), and after the algebraic manipulations one obtains \[16]:

\[
\sum_{G}[\eta(\vec{G}-\vec{G}')]|\vec{K}+\vec{G}'|^2 + \xi(\vec{G}-\vec{G}')]E_{K}(\vec{G}') = \left(\frac{\omega}{c}\right)^2 E_{K}(\vec{G}'.)
\]

(5)

where \( G \) and \( G' \) are the reciprocal lattice vectors, \( \vec{K} \) is Bloch wave vector, \( \xi(\vec{G}) \), \( \eta(\vec{G}) \) and \( E_K(\vec{G}) \) are the Fourier transformation of \( \eta(\vec{r}) \), \( \xi(\vec{r}) \) and \( E_K(\vec{r}) \), respectively. This equation gives information about the existence of the line defect modes within the photonic band gap (See Ref. [16] for further details). These modes were appeared to lie in frequency regions where wave propagation is forbidden in the infinite crystal [18]. In Fig. 2, the photonic band structure and waveguide modes have been plotted for various temperatures of the superconductor. This figure indicates that for each temperature, one waveguide mode exists within the PBG, and the position of these modes apparently moves down as the temperature of the superconductor increases.

Then the FDTD method was employed directly to solve Maxwell's equations in the time domain and calculate the field distribution and coupling efficiency. A plane wave has been launched at the 16a away from the left of PCW in the normalized frequency \( 0.344 \, a/\lambda \), with the width of 25a (the frequency which is the nearly the maximum transmission of SeCPC occurs [13]). It is notable that the attention is focused on the far-infrared region. Lattice constant of the structure is set to be 250 \( \mu m \) [14]. The structure is surrounded by perfectly the match layers (PMLs) as absorbing boundary conditions to truncate the computational region and to avoid the reflections from the outer boundary. The scale of the SeCPC is 13a in X and Y direction, i.e., the SeCPC structure contains 13 concentric semi-circles. The square lattice PCW stretches out 22 and 26 periods along the x and y directions, respectively. The spatial resolution of FDTD in a unit cell is set to 21, and PML involves 12 grids which are sufficient to prevent the back reflections. Self writing code was applied in MATLAB for the mentioned and stated FDTD simulation. The coupling efficiency, \( \eta \), could be expressed as the ratio of the light propagated intensity in the presence of the waveguide to its value in the absence of the waveguide [12]. The integrals were carried out over the waveguide, where the light propagated (see right side of Fig. 5):

\[ \eta = \frac{\int_{-13.5a}^{13.5a} \int_{-33.8a}^{34.2a} |E_{z\text{PCW+SeCPC}}|^2 \, dxdy}{\int_{-13.5a}^{13.5a} \int_{-33.8a}^{34.2a} |E_{z\text{PCW}}|^2 \, dxdy}. \]

Through the Fig. 3, the coupling efficiency, \( \eta \), was depicted as a function of the temperature of the superconductor for different values of the superconductor rods radii. The accessed results indicate that the coupling efficiency is strongly temperature-dependent. It is important to know that the efficiency decreases initially as the temperature increases for all cases, but for further increase through the temperature, it can be seen that the efficiency takes a peak value and finally it vanishes approximately as the temperature approaches to the critical value. The result of the presented figure can be compared for the case of \( R=0.2a \) with Fig. 2 in which the crossing point of our employed source frequency (0.344 \( a/\lambda \)) with the waveguide modes has been examined. As it has been plotted in Fig. 2, it can be concluded that a fall between initial value and the peak one of the efficiency corresponds to large
group-velocity dispersion of waveguide modes which deforms optical pulses severely. There is no crossing point above the temperature 80 K and consequently the coupling efficiency is vanished in this region.

Moreover, as a reader may attend, with the variation of the waveguide sizes, not only the peak value is shifted, but also it increases slowly because of the variations of the crossing point of the source frequency as it was mentioned before. The benefit of the presented feature is that one can obtain high values of the efficiency at the desired temperatures. For example, it is possible to choose the superconductor rods as 0.23a in which the maximum efficiency occurs at T=77 K. It is worth to mention that at 61.5 K temperature, the dielectric constant of the superconductor approaches to unit (same as the background), hence the size of the rods becomes irrelevant.

Now, as it has been motivated by the cited feature in which the efficiency is changed by the size of the waveguide, the size effect of the adjacent rods of the waveguide was studied in base of efficiency. Fig. 4 illustrates the coupling efficiency versus the temperature for various values of the neighbor rods’ sizes (R1 and R2 are radius of the first and second adjacent rods, respectively). It can be seen that by increasing the first neighbor’s rod sizes to 0.25a, the maximum of the coupling efficiency reached to 8.32 (while it was 7.89 in the absence of variations) and by decreasing of the second nearest neighbor rods sizes to 0.14a it is possible to obtain the 10.7.

As the results can be seen through the Fig. 5, to get more insight into the coupling, the intensity distributions are simulated. It can be understood that the energy would transfer from the SeCPC to the waveguide could be prohibited at 90 K, while light flow in the waveguide could be barely seen at 75 K, and both of them are correspond to the low and high coupling efficiency, respectively.

4. Conclusion

In sum, the researchers numerically studied and investigated the optical coupling between a superconductor waveguide and SeCPC in two-dimensional PhCs by using the plane wave expansion (PWE) method and finite-difference time-domain (FDTD) method. The effect of superconducting waveguide size and its two nearest neighbor rods sizes were analyzed and studied on the coupling efficiency. Of course, it is necessary to mention that coupling efficiency includes a peak in the middle temperatures and it approximately vanishes as the temperature of the superconductor approaches to the critical temperatures. Moreover, it was realized and depicted that high coupling efficiency could be obtained by suitable choice of the radius of the adjacent rods of the waveguide. The results also met an important condition which showed the
necessity of picking the smaller size of superconducting waveguide to get the maximum efficiency in higher temperatures. The mentioned feature may be useful in the application of the structures above the liquid nitrogen temperature.

References


