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# 1×2 Optical Drop Splitter in a Rod-type Silicon Photonic Crystal

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**Abstract**: Based on a self-collimation ring resonator (SCRR) in a rod-type silicon photonic crystal, a 1×2 optical drop splitter (ODS) with selected splitting ratio is proposed. The 1×2 ODS consists of three beam splitters and one mirror, and light propagates in the ODS employing self-collimation effect. The theoretical transmission spectra at different drop ports of the ODS are analyzed with the multiple-beam interference theory, and they were investigated with the finite-difference time-domain (FDTD) simulation technique. The simulation results agree well with the theoretical prediction. For the drop wavelength 1 550 nm, the free spectral range of the ODS is about 30 nm, which almost covers the whole optical communication C-band window. Because of their small dimensions and whole-silicon material, the proposed ODSs hold great potentials for applications in photonic integrated circuits (PICs).

**Key words**: Photonic Crystal (PhC); Self-Collimation (SC); Optical Drop Splitter (ODS)
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## 0 Introduction

Photonic crystals (PhCs)[1-3], composed of periodic dielectric materials, have attracted great attention due to their unique ability to manipulate light. The distinguished properties of PhCs, such as superprism effect[4], negative refraction[5], and self-collimation (SC) effect[6-11] have been extensively studied. SC effect allows light propagation without diffraction in perfect PhCs without "physical" guiding boundaries (e. g. line-defect waveguide)[8]. Additionally, it can also enable two beams intercrossing without cross-talks. A variety of photonic devices based on SC effect have been proposed including Fabry-Perot etalons[12], Mach-Zehnder interferometers[13-14], and our recently proposed self-collimation ring resonators (SCRRs)[15] etc.

In this paper, based on an ultra-compact SCRR in a rod-type silicon photonic crystal, we put forward an approach to perform an 1×2 optical drop splitter (ODS) by properly making three beam splitters of the SCRR. It is evident that light absorption from silicon can be negligible according to P. T. Rakich′s experiments[16]. The self-collimation frequency range of the PhC for TM polarization was firstly figured out, followed by the theoretical description of 1×2 optical drop splitters based on the theory of multiple-beam interference. Furthermore, the performance of the proposed ODSs was numerically analyzed by using two-dimensional (2D) finite-difference time-domain (FDTD) technique, and the simulation results are in well agreement with the theory.

## 1 Design and calculations

### 1.1 Self-collimation frequency ranges in 2D rod-type PhC

A 2D silicon (Si) PhC we considered consists of a square lattice of dielectric cylindrical rods in air, where the dielectric constant $\varepsilon_{Si}$ and the ratio of the cylindrical radius $r$ to the lattice constant $a$ are 12.25 and 0.39, respectively. The simulated dispersion curves of the first band along $\Gamma M$ direction for TM polarization (transverse-magnetic) is shown in Fig. 1.

The corresponding equal frequency contours (EFCs) in one fourth of the first Brillouin zone are also shown in Fig. 2. All the calculations are done by the plane-wave expansion (PWE) method[17]. As shown in Fig. 2, the EFCs in the frequency range between $0.175c/a$ and $0.195c/a$ are close to

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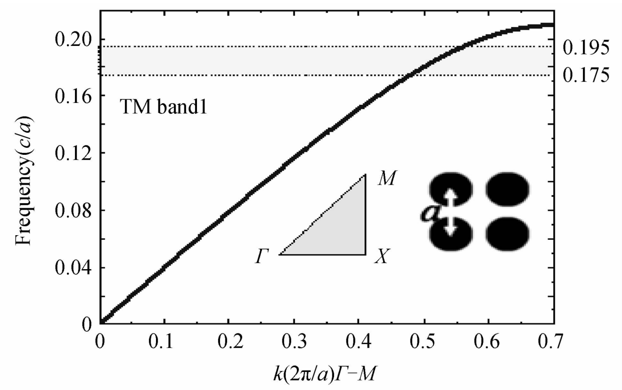



Fig. 1 Curve of the first band along $\Gamma M$ direction for TM polarization in the 2D square-lattice rod-type silicon PhC

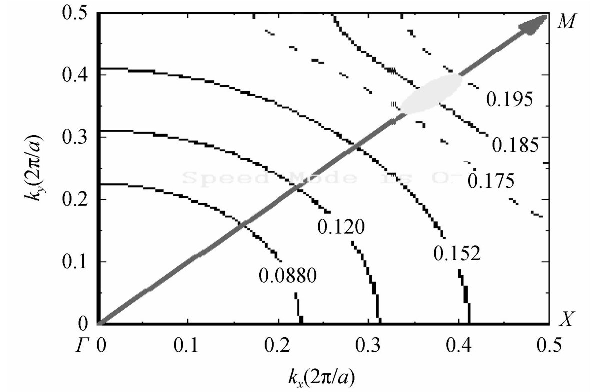



Fig. 2 Equal frequency contours of the first band (the highlighted regions between two dash lines correspond to the SC frequency window)

straight lines normal to the $\Gamma M$ direction (where $c$ is the speed of light in vacuum). Hence, at these frequencies and in the direction perpendicular to the flat EFCs, light can propagate within the PhC without diffraction, which is known as self-collimation effect.

### 1.2 1×2 ODS based on SCRR

The proposed 1×2 ODS based on a SCRR is shown in Fig. 3, which consists of three beam splitters (BSs) and one mirror. Each BS is a line defect formed by reducing the radius of one row of 23 cylindrical rods in the $\Gamma X$ direction, from normal $r=0.39a$, to $r_s$, e. g. $0.313a$, determined by the splitting ratio requirement. The mirror is formed by inserting an air bar along the $\Gamma X$ direction, overlapping two rows of 24 cylindrical rods. As shown in Fig. 4, the reflectivity of the mirror $R_M$ is vey close to 100% from $0.175c/a$ to $0.195c/a$. There are one input port, one through port and two drop ports in the ODS. When a SC light beam with intensity $I_0$ is launched into the input port, the $BS_1$ will split the light beam into two parts, the reflected beam and the transmitted beam. The transmitted light keeps the original direction and propagates into $BS_2$ while the reflected light comes out from the through port. The similar behavior happens in the $BS_2$ and $BS_3$, and the mirror almost reflects the whole SC light.

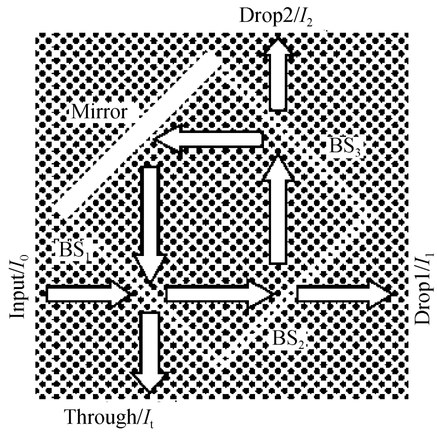



Fig. 3 Structure of the proposed 1×2 optical drop splitter consisting of three different beam splitters ($BS_1$, $BS_2$, and $BS_3$) and one mirror

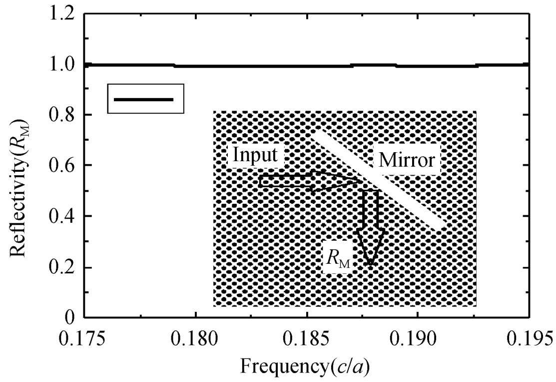



Fig. 4 Simulated reflection spectra of the mirror in the self-collimation frequency range where the arrows in the inset indicate the directions of light propagation

We suppose the reflectivity of $BS_1$, $BS_2$ and $BS_3$ are $R_1$, $R_2$, and $R_3$, respectively. According to the theory of multiple-beam interference[18], the equations for the transmission spectra at the through and drop ports can be expressed as

$$\frac{I_t}{I_0}=\frac{R_1+R_2R_3-2\sqrt{R_1R_2R_3}\cos\varphi}{1+R_1R_2R_3-2\sqrt{R_1R_2R_3}\cos\varphi} \tag{1}$$

$$\frac{I_1}{I_0}=\frac{(1-R_1)(1-R_2)}{1+R_1R_2R_3-2\sqrt{R_1R_2R_3}\cos\varphi} \tag{2}$$

$$\frac{I_2}{I_0}=\frac{(1-R_1)R_2(1-R_3)}{1+R_1R_2R_3-2\sqrt{R_1R_2R_3}\cos\varphi} \tag{3}$$

where $I_0$ is the intensity of the input light, $I_i$ ($i=1, 2$) represent the light intensity at a drop port and $I_t$ is the light intensity at the through port. $\varphi$ is the phase delay after one-loop beam propagation in the SCRR which can be expressed as

$$\varphi=kl_e+\theta \tag{4}$$

where $k$ is the Bloch wave vector, based on the dispersion curve ($k=k(f)$) as shown in Fig. 1, *and* $l_e$ is the effective propagation distance of one loop for SC light. $\theta$ is the total phase shift resulting from the phase jump at the beam splitters and the mirror. From equations (1)～(3), when the phase delay $\varphi = 2j\pi$ ($j$ is an integer), the transmissions at two drop ports reach their peak values while the transmission at the through port reaches its minimum value, which is so-called resonance effect. The corresponding light frequencies are called resonance frequencies, or drop frequencies. Again from equation (1), when $\varphi=2j\pi$ and $R_1+R_2R_3=2\sqrt{R_1R_2R_3}$, $I_t=0$, which means that light with drop frequencies can get out of the SCRR totally from two drop ports. Thus the SCRR can work as an 1×2 ODS. In addition, we can get different splitting ratios for the two drop ports at drop frequencies by selecting the reflectivity $R_i$ of each beam splitter properly while keeping $R_1+R_2R_3=2\sqrt{R_1R_2R_3}$. For example, $I_1 : I_2 = 1 : 1$ when $R_1=0.4$, $R_2=0.7$, $R_3=4/7$, and $I_1 : I_2=1 : 2$ when $R_1=0.4$, $R_2=0.8$, $R_3=0.5$. In fact, we can get various splitting ratios for 1×2 photonic drop splitters.

In order to get the 1×2 ODSs with different splitting ratios, the performance of a beam splitter is first evaluated numerically with the 2D FDTD method. As shown in Fig. 5(a), a Gaussian optical pulse covering frequency range [0.175$c/a$, 0.195$c/a$] is launched in the $\Gamma M$ direction to the beam splitter. The powers of the incident, transmitted and reflected SC light are recorded with three power monitors. By normalizing the transmitted and reflected powers to the incident power, the transmissivity $T_s$ and the reflectivity $R_s$ can be figured out. Fig. 5(a) shows the transmissivity and the reflectivity of a beam splitter vary with frequency when $r_s=0.298a$ while Fig. 5(b) shows the transmissivity $T_s$ and the reflectivity $R_s$ vary with $r_s$ at frequency $f=0.187\,4c/a$. The reflectivity decreases sharply when $r_s$ increases. It can be seen that $R_s\approx 0.5$ when $r_s=0.298a$.

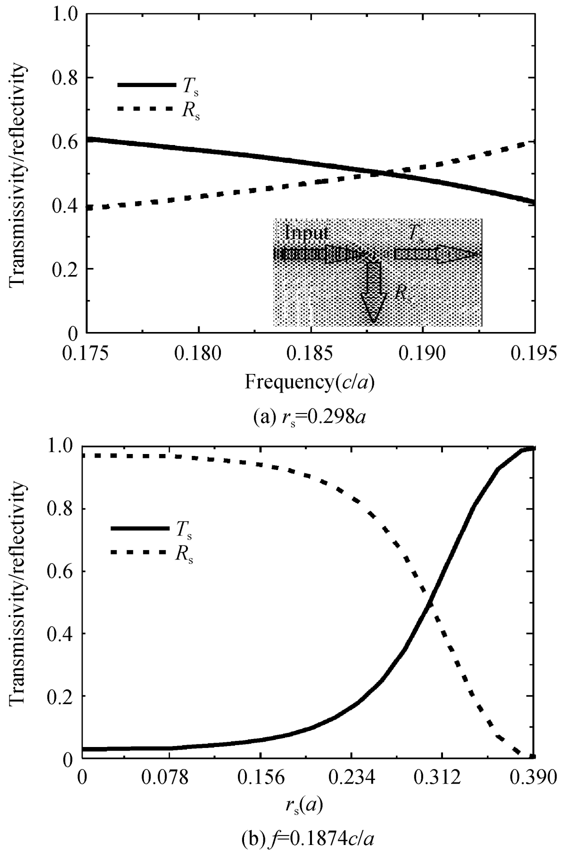



Fig. 5　$T_s$ and $R_s$ of the beam splitter vary against frequency and $r_s$

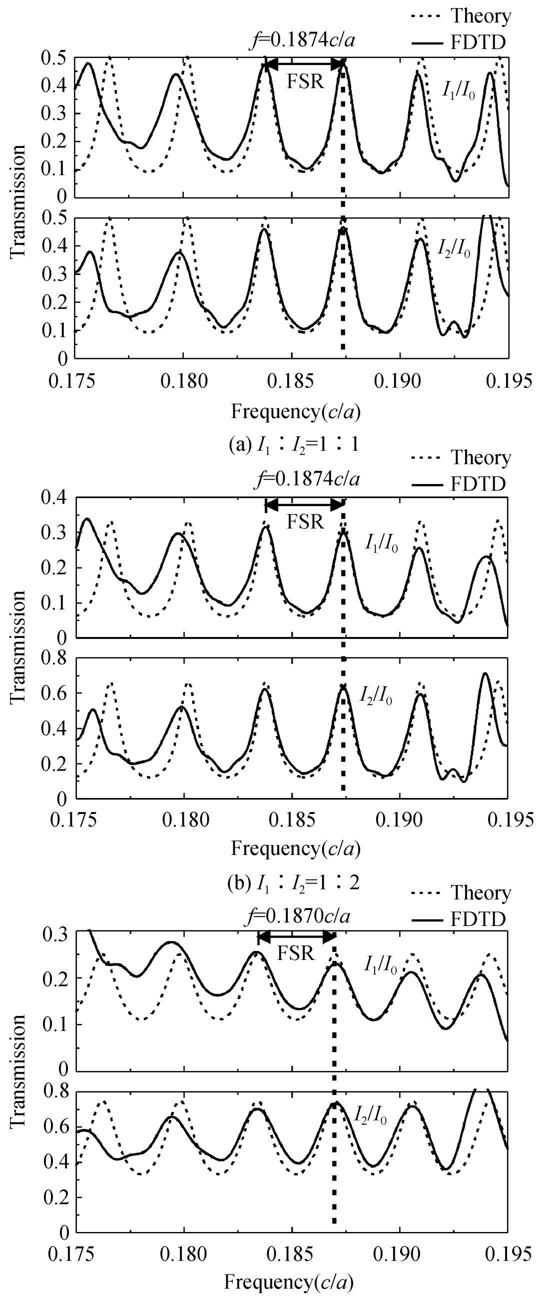
From above discussions, it is possible to design 1×2 ODSs with interesting splitting ratios for the two drop ports. Table 1 shows the selected reflectivity $R_i$ and corresponding cylindrical rods radius $r_{si}$ of each beam splitter for the 1×2 ODSs with splitting ratios 1 : 1, 1 : 2 and 1 : 3.

**Table 1　Selected parameters for three specific 1×2 ODSs with different splitting ratios**

| Splitting ratio ($I_1 : I_2$) | $R_1$; $r_{s_1}$ | $R_2$; $r_{s_2}$ | $R_3$; $r_{s_3}$ | $l_e$ | $\theta$ | Drop frequency |
|---|---|---|---|---|---|---|
| 1 : 1 | 0.4; 0.313$a$ | 0.7; 0.268$a$ | 4/7; 0.290$a$ | $45\sqrt{2}a+0.88\sqrt{2}a$ | 3.18$\pi$ | 0.1874$c/a$ |
| 1 : 2 | 0.4; 0.313$a$ | 0.8; 0.244$a$ | 0.5; 0.301$a$ | $45\sqrt{2}a+0.81\sqrt{2}a$ | 3.23$\pi$ | 0.1874$c/a$ |
| 1 : 3 | 0.2; 0.338$a$ | 0.8; 0.244$a$ | 0.25; 0.333$a$ | $45\sqrt{2}a+0.83\sqrt{2}a$ | 3.32$\pi$ | 0.1870$c/a$ |

To verify the theoretical design of the three 1×2 ODSs, the numerical transmissions at drop ports for TM modes are also simulated with the 2D FDTD method. A $5\sqrt{2}a$-width Gaussian optical pulse which is located $2\sqrt{2}a$ away from the edge of the photonic crystal structure is launched at the input port. The input power ($I_0$) and each drop power ($I_i$) are monitored with power monitors. The drop transmission spectra ($I_i/I_0$) are plotted in Fig. 6 (a)～(c) as solid lines for the three ODSs respectively. In Fig. 6(a), the transmission values at two drop ports for the drop frequency $f=0 : 187\,4c/a$ are both equal to 0.473. So the SCRR can work as a 1×2 ODS with splitting ratio 1 : 1. In Fig. 6(b), the transmission values at two drop ports for the drop frequency $f=0.187\,4c/a$ are equal to 0.315 and 0.632, respectively. So the SCRR can also work as a 1×2 ODS with splitting ratio 1 : 2. And in Fig. 6(c), the transmission values at two drop ports for the drop frequency

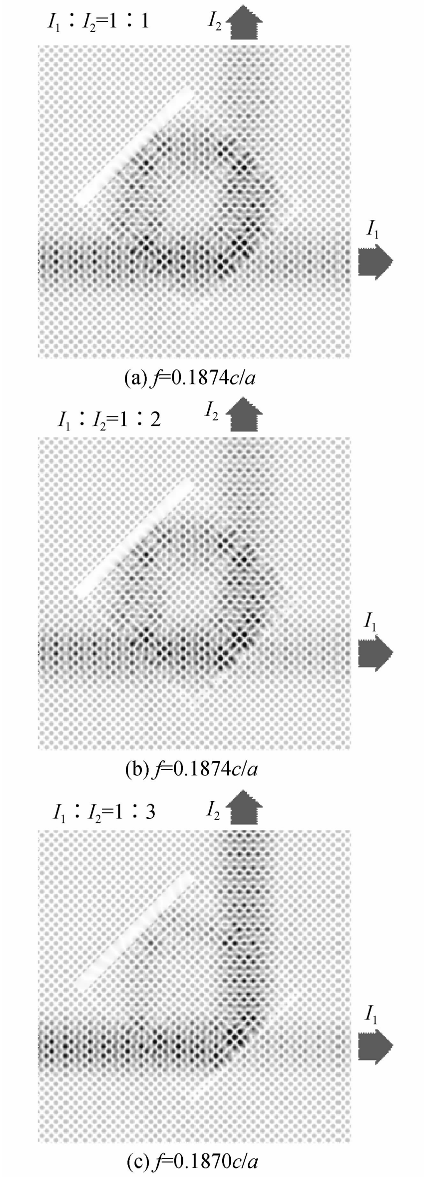
$f$=0.1870$c/a$ are equal to 0.230 and 0.750, respectively. Now the SCRR can work as a 1×2 ODS with splitting ratio 1∶3. It should be pointed out that the simulated transmission values are somewhat lower than the theoretical ones. For $I_1:I_2=1:1$, $I_1:I_2=1:2$ and $I_1:I_2=1:3$, the theoretical transmission values at resonance frequencies should be 0.5∶0.5, 0.333∶0.667 and 0.250∶0.750 for two drop ports respectively. It indicates that propagation loss exists which may result from the scattering in the line-defect beam splitters.




(a) $I_1:I_2=1:1$ (b) $I_1:I_2=1:2$ (c) $I_1:I_2=1:3$

Fig. 6 Theoretical and FDTD simulated transmission spectra of the 1×3 photonic drop splitters with different splitting ratios

The theoretical transmission spectra according to equations (2) and (3) are also plotted as dash lines in Fig. 4. Note that the total phase shift $\theta$ after one loop should be in range of $2\pi$ and $4\pi$ [7] and its exact value can be achieved based on the best fit between FDTD simulated and theoretical transmission spectra [15]. We can find that the simulation curves agree well with the theoretical curves in terms of peak positions when $\theta=3.18\pi$ for $I_1:I_2=1:1$, $\theta=3.23\pi$ for $I_1:I_2=1:2$ and $\theta=3.32\pi$ for $I_1:I_2=1:3$. The electric field distributions for the drop frequencies were also simulated and shown in Fig. 7. Notice that there is no light exiting from the through port. In addition, for the drop wavelength 1 550 nm, the




(a) $f$=0.1874$c/a$ (b) $f$=0.1874$c/a$ (c) $f$=0.1870$c/a$

Fig. 7 Magnetic-field distributions of the steady-state electric field of designed 1×2 optical drop splitters at the drop with different frequencies (notice: there is no light coming out from the through port) free spectral range (FSR) of the 1 × 2 ODSs is about 30 nm, which almost covers the whole optical communication C-band window.

## 2 Conclusions

In conclusion, we proposed 1×2 optical drop splitters based on self-collimation ring resonators in a silicon-rod photonic crystal. The photonic drop splitters with various splitting ratios for the two drop ports can be designed by selecting the reflectivity of the three beam splitters properly. The simulated results by using 2D FDTD agree well with the theoretical calculations based on the principle of the multiple-beam interference. For the operating wavelength 1 550 nm, the dimensions of this structure are only about 10 μm which offers potential applications in the high-intensity photonic integrated circuits.

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# 基于圆柱型硅光子晶体的1×2光下路分束器

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**摘　要**:本文设计了一个基于圆柱型硅光子晶体自准直环形腔的1×2光下路分束器.该光下路分束器由三个分光镜和一个反射镜构成,其中窄光束依赖自准直效应进行传输.利用多光束干涉理论分析了光下路分束器中不同出口的理论透射谱,并且利用时域有限差分法对光下路分束器透射谱进行数值模拟计算,其结果与理论预测基本一致.当下路波长为1 550 nm时,光下路分束器的自由光谱范围约为30 nm,几乎涵盖了整个光通信C波段.由于其小尺寸和全硅材料,本文设计的1×2光下路分束器有望应用于未来的集成光路中.

**关键词**:光子晶体;自准直;光下路分束器