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اثر کوپلینگ ناقص بر انتشار نور کُند در موجبر بلور فوتونی حلقه‌ای شکل

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چکیده – در مدارهای فوتونیکی، خطوط ارتباط نوریِ بستر، معمولا موجبرهای ریب هستند. مسئله‌ی کوپلینگ موثر بین موجبرهای نورکند و موجبرهای ریب یکی از مسائل چالش برانگیز است که تاکنون توجه زیادی را به خود جلب کرده است. پیش از این تحقیقات فراوانی بر روی کوپلینگ موثر انجام گرفته در حالی که اثر کوپلینگ ناقص بر انتشار نورکند در موجبرهای بلور فوتونی بررسی نشده است. در این مقاله از ساختار بهینه شده موجبر بلور فوتونی حلقه‌ای شکل استفاده شده است و اثرات کوپلینگ ناقص را بر روی انتشار نور کند در این گونه موجبرها مورد بررسی قرار گرفته است. نتایج شبیه‌سازی نشان می‌دهند که قسمت زیادی از تلفات انتشار به دلیل کوپلینگ ناقص است. از سوی دیگر، اثر جمع آثار موج‌های بازتابشی از محل کوپل‌شدگی به داخل موجبر، باعث رفتار غیرمنظم نور کند می‌شود که محاسبه‌ی تلفات و ضریب شکست گروه را تحت تاثیر قرار می‌دهد.

کلید واژه- موجبر بلور فوتونی، کوپلینگ ناقص، نور کند، بافر نوری.

The Effect of Incomplete Coupling on Slow Light Propagation in Ring-shape-hole Photonic Crystal Waveguide

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Abstract- In photonic circuits, the substrate optical connections are usually realized by the Rib waveguides. The effective coupling between the slow light waveguides and the Rib waveguides is a major challenge which has been an interested research topic. Previously, several researches were conducted on the effective coupling while the incomplete coupling effects on the slow light propagation in the Photonic Crystal Waveguides (PCW) are not investigated so far. In this paper, an optimized structure of the ring-shape-hole PCW is utilized in order to investigate the effects of incomplete coupling on the slow light propagation. The simulation results show that a considerable portion of the propagation losses is caused by the incomplete coupling. On the other hand, the superposition of the waves reflected to the waveguide causes the irregular behavior of slow light. According to results, this phenomenon affects the calculation of the loss and the group index.

Keywords: Photonic Crystal Waveguide, Incomplete Coupling, Slow Light, Optical buffer.

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Abstract: *In photonic circuits, the substrate optical connections are usually realized by the Rib waveguides. The effective coupling between the slow light waveguides and the Rib waveguides is a major challenge which has been an interested research topic. Previously, several researches were conducted on the effective coupling while the incomplete coupling effects on the slow light propagation in the Photonic Crystal Waveguides (PCW) are not investigated so far. In this paper, an optimized structure of the ring-shape-hole PCW is utilized in order to investigate the effects of incomplete coupling on the slow light propagation. The simulation results show that a considerable portion of the propagation losses is caused by the incomplete coupling. On the other hand, the superposition of the waves reflected to the waveguide causes the irregular behaviour of slow light. According to results, this phenomenon affects the calculation of the loss and the group index.*

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1 Introduction

Over the last decade, there has been a growing interest in utilizing Photonic Crystal (PC) due to its wide range of applications. The slow light in Photonic Crystal Waveguide (PCW) is one of the attractive subjects for realizing slow light at room temperature [1]. PCW has been used in nonlinear optics [2], time-domain signal processing [1], and all-optical buffers [3]. There are many theoretical and experimental researches in the literature focusing on slow light in line defect PCWs [4], and most of them, pursued designing the PCWs. The main factor usually considered to evaluate the PCW designs is the Normalized Delay-Bandwidth Product, NDBP. In most of designs, the objective is to maximize the NDBP value.

The PCW, as a device, is exploited in photonic circuits in which the optical connections between different devices are usually constructed by the Rib waveguides. The Coupling between Rib waveguide and PCW is an important issue must be noted due to the effects on slow light time domain calculation and attenuation of optical signals.

Several researches were conducted on the coupler design [5]. But the incomplete coupling was not investigated clearly in any of the previous works. Therefore, in this paper the incomplete coupling between the Rib waveguide and the PCW is studied and its effects on the calculations of the time domain analysis are presented.

The paper is organized as follows. In Section 2, the considered PCW structure is presented. The simulations of the time domain in PCW are investigated in Section 3. Section 4 provides the numerical results. The paper concludes in Section 5.

2 Ring-Shape-Hole PCW (RPCW) structure

In this paper, we use our previously proposed RPCW structure [6].This optimized structure is obtained by using particle swarm optimization algorithm in order to maximize NDBP [6]. As a convenient review, the structure and characteristics of the proposed PCW are provided in Fig. 1 and Table 1, respectively. The thickness of the silicon slab of SOI is 400nm. So, the slab equivalent index for 2D calculation is equal to 3.18 [6].

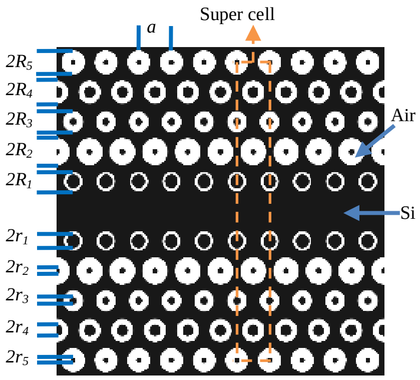

Figure 1: The previously proposed RPCW structure with super cell [6].

Table 1: Structural parameters of RPCW, [6].

Parameter	*Value*	*Parameter*	*Value*
R_1 (nm)	105	r_3 (nm)	38
R_2 (nm)	147	r_4 (nm)	59
R_3 (nm)	113	r_5 (nm)	0
R_4 (nm)	126	a (nm)	367
R_5 (nm)	131	λ_0 (nm)	1550
r_1 (nm)	71	n_{g_avg}	29.2
r_2 (nm)	28	$\Delta\lambda$ (nm)	32.6
NDBP	0.61		

3 Time domain Analysis of slow light propagation in RPCW

The design of PCWs is always done by Plain Wave Expansion (PWE) method. This method calculates the group index (n_g) and bandwidth ($\Delta\lambda$) of PCWs. However, the pulse broadening and attenuation are also major issues must be taken into account in PCW design. But, the PWE method can't calculate these parameters. Therefore, the Finite Difference Time Domain (FDTD) method is utilized to simulate the optical pulse propagation in PCWs.
For this purpose, some monitor points are placed in the pulse propagation direction in PCW. Then, the detected electric field can be plotted versus the time elapsed with the pulse propagation. As a result, the group velocity, the power loss and the pulse broadening can be calculated.According to [7], the group index of the RPCW can be calculated using Equation (1) in which $\bar{v}_g$ is the group velocity average, Δx is the distance between input and the observe point, ΔT is the time that the wave travels between input and observe point.

$$\bar{v}_g = \frac{\Delta x}{\Delta T} = \frac{c}{\bar{n}_g} \rightarrow \bar{n}_g = \frac{c\Delta T}{\Delta x} \qquad (1)$$

4 Numerical results and discussion

In this section the results are given to verify the performance of RPCW. The FDTD method is applied to simulate the optical pulse propagation in 50a-length RPCW. We utilize a Gaussian pulse centered at λ_0=1550nm with the bandwidth ($\Delta\lambda$) of 32.6nm. The optimized RPCW with 11 field monitors is depicted in Fig. 2.
Two positions are simulated: the complete coupling case and the incomplete coupling between the RPCW and the Rib waveguide. The field waveforms for the mentioned cases are shown in Fig. 3 and Fig. 4, respectively. Fig. 4 shows that the power of Gaussian pulse is almost gradually decreased along the waveguide same as Fig. 3. The interesting event is the significant decrease in the field amplitude from the tenth field monitor to eleventh field monitor. This rapid amplitude reduction is due to incomplete coupling between the RPCW and the Rib waveguide. It is worth mentioning that the effect of incomplete coupling between the Rib and PCW is not shown at input, because of the absence of the field monitor at the PCW input. By comparison of all waveforms, the amplitude of the waveforms in field monitors 8, 9, and 10 does not follow homogeneous behavior. In other words, the amplitudes of the waveforms in the eighth and tenth field monitors are higher than the expected amplitudes, whereas the amplitude of waveform in the ninth field monitor is lower than the estimated value. This is again because of the incomplete coupling between RPCW and Rib waveguide. It means that a portion of the power of the optical pulse is reflected from the coupled area and comes back to the waveguide. Consequently, the superposition effect of the incident wave with the reflected wave causes the exceptional behavior.
In Fig. 5, the delay time of the envelope maximum of all waveforms is plotted versus its filed monitor position. According to Equation 1, the slope of the fitted linear curve between all points is equal to $\bar{n}_g$. The FDTD calculation results for the optimized RPCW structure are presented in Table 2. As shown, we have $\bar{n}_g$ =26.3 which is totally compatible with the $\bar{n}_g$ =29.2 calculated by PWE method. The slight discrepancy is caused by the intrinsic error of the PWE method.
In order to determine the attenuation and distortion in RPCW, we have to consider the waveforms with the minimum aforementioned coupling effect. In

our case, we consider the third field monitor as input and the seventh field monitor as output. The comparison of Full Width at Half Maximum (FWHM) of the third and seventh field monitors shows the pulse broadening in a unit of length is very low (2.6% (1/µm)). Moreover, the attenuation in a unit of length is equal to 0.27dB/µm. Therefore, it is clear that the optical pulses propagate with low distortion and low attenuation in the optimized structure.

5 Conclusion

In this paper, the effects of the incomplete coupling between the RPCW and the Rib waveguide were investigated. The simulation results showed that the incomplete coupling has a remarkable effect on the loss. On the other hand, the reflected waves from the coupling point make superposition with the incident waves and cause an irregular behaviour in slow light. The precise evaluations showed that despite the incomplete coupling, the group index and the slow light propagation loss can be calculated.

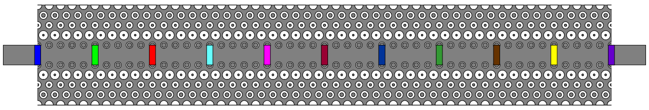

Figure 2: The optimized RPCW with 11 field monitors

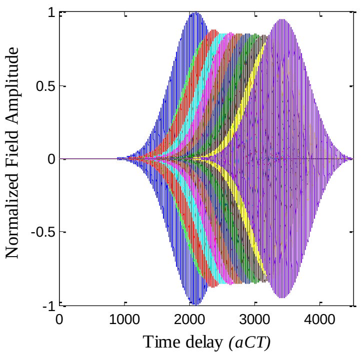

Figure 3: Detected waveforms corresponded to the same colored field monitor of Fig. 2 (complete coupling case)

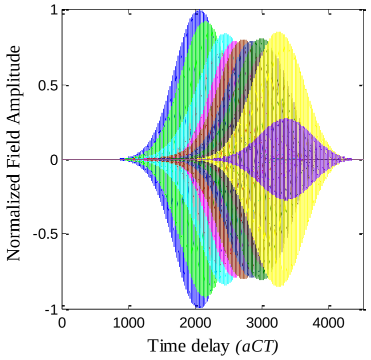

Figure 4: Detected waveforms corresponded to the same colored field monitor of Fig. 2 (incomplete coupling case)

Table 2: FDTD calculation results of the optimized RPCW

Time domain parameters	*Calculation results*
$\bar{n}_g$	26.3
FWHM(Field Monitor 3)	368 (aCT)
FWHM(Field Monitor 7)	440 (aCT)
Pulse broadening in a unit of length	2.6 % (1/µm)
Attenuation in a unit of length	0.27 (dB/µm)

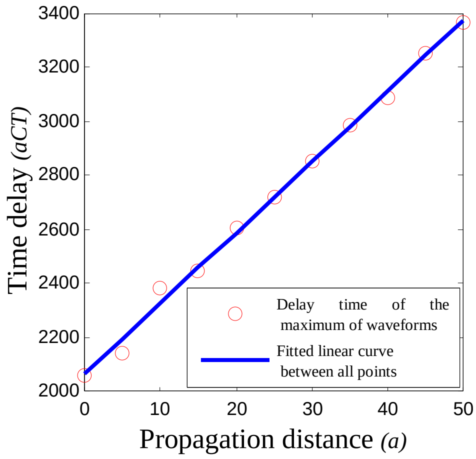

Figure 5: Delay time of the envelope maximum of all waveforms versus its filed monitor position (incomplite coupling condition)

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