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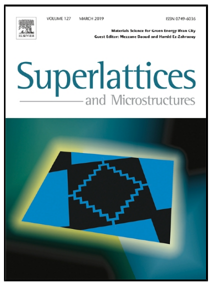

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Light Amplification in Cascaded Silicon Structures

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Abstract- In this paper we propose an integration of an amplifier and a filter in a single ultra-compact photonic crystal (PC) platform. The proposed platform consists of three PCs of different air holes radii with the same lattice constant *a.* The PC in the center of the platform is constructed of D-shapes which contain defects with different shapes, used as a central building block for photonic amplifier. We show that by cascading three PC building blocks, the output signal increases to almost 90% when the control beam is ON, whilst it drops to less than 20% when the beam is switched OFF. Our proposed structure would play a significant role on designing future highly-integrated optical communications chip-to-chip quantum computing and photonic information processing.

***Index Terms*-Optical platform, Active region, Light amplification, ultra-compact circuit.**

I. INTRODUCTION

Photonic devices with high optical out power and bandwidth are key components for building blocks of modern all-optical information processing computers. As the optical signal propagates through different waveguides and media, the light experiences various losses and scattering which leads to attenuations and distortions due to its matter nature [1, 2]. In the past two decades intensive studies have been conducted to understand light-matter interactions and explore its novel materials properties. Many researchers have proposed various schemes to design photonic devices based on engineering new materials [3- 5]. Several optical devices with footprints less than the operating wavelength, are proposed based on these engineered materials [5-8]. The emergence of silicon nano-photonics [9-16] paves the way for designing on-chip large-scale integrated optical elements. The active element are considered as the fundamental building blocks for the future quantum computing Central Processing Unit (CPU), although optical losses and light amplification remains a challenging matter that needs further investigations [17]. To overcome these losses which are generated when the signal propagates through the coupled PCs, the cascading of two or more PC building blocks is necessary to increase the gain. Through the coupling of two structures, the optical signal can be controlled and manipulated to reach the output port without attenuation [18]. Using coupled PCs structures with modified linear defects would enable creative ways to develop ultra-compact all-optical systems. In this research work, we have proposed geometrical configuration scenarios of optical amplifiers and filters in multifunctional all-optical platform based on linear defects and by means avoiding implementation of nonlinear materials. In this work, we use three coupled PCs, the central PC contains three ports operating as control beam to design amplifier (100%) and a filter (< 20%) as ultra-compact metadevices. The proposed integrated PC structure can be fabricated with existing manufacturing capabilities. In order to demonstrate the proposed design, we have deployed in-house finite difference time domain (FDTD) method to design the proposed integrated optical amplifier and filter. The proposed structure may constitute an important step for future potential applications in all-optical ultra-compact computing devices.

II RESULTS AND DISCUSSION

The proposed structure consists of three coupled PCs, indicated as PC1, PC2 and PC3. The PC1 and PC3 consisting of air holes with radii r_1 = 0.25s and r_3 = 0.36s. The active region is sandwiched between PC1 and PC3, contains three ports used as control beams (ON/OFF). The guiding region is created by modifying the sizes of the D-defects along the array. The parameters of the guiding region are illustrated in figure 1. The background is composed of Si with $\varepsilon_{si} = 11.56$.

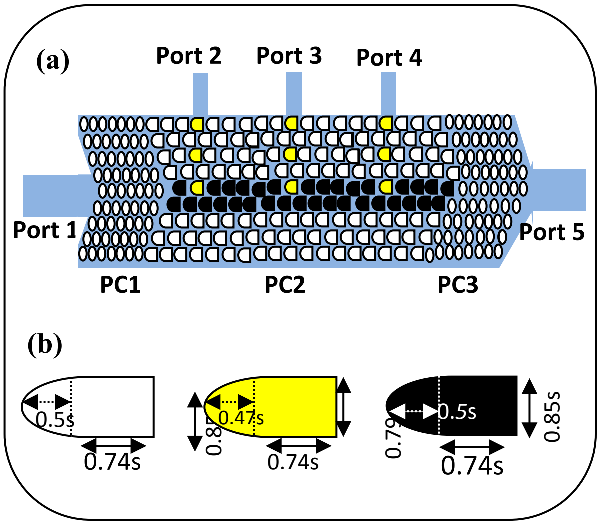

Fig. 1a. Schematic of the proposed amplifier and filter metadevice: PC1 and PC3 are composed of air holes, while PC2 is composed of "D" shapes, the guiding region is realized by reducing the size of the defect D, (b). The guiding region composed of D-defects with different sizes.

In Fig. 1b, the guiding region composed of "D" shape. These shapes are of different sizes, the white- D-shape is composed of a rectangular of size sx0.85s and a half circle of a radius r = 0.47s, the yellow defect consists of a rectangular 0.74sx0.79s and a semi-circle of radius r = 0.47s. While the circle in black-D defect is reduced, where the radius r = 0.5s, where s is the lattice step.

In proposed model, silicon Si substrate, is chosen because of its long time use in microelectronics, also due to the miniaturization is more controlled flexibility [19]. The Gaussian sources were used for FDTD method [20], the spatial discretization steps are chosen as $\Delta x = \Delta y$ = s/20, the Perfect Matched Layers (PMLs) region with 20 cells is used as a boundary condition in z-direction. The Gaussian sources are launched in ports 1, the usage of the control beam to the gate flip flop (ON/OFF: port 2, 3 and 4) allows the source and the control beam to match then an amplification of the light is attended at port 5. In order to register the light intensity at port 5, monitors are placed at the output section of the structure.

Firstly, we launch the signal through input port 1 and the control beam in ports 2, 3 and 4 is ON. The snapshots are represented in figure 2a. The light intensity is calculated and illustrated in figure 2b, the maximum is about 96%. Next, we switch the control beam OFF and we inject the signal in port 1, the snapshots are shown in figure 3a, it is observed that the signal is weak and no amplification is observed.

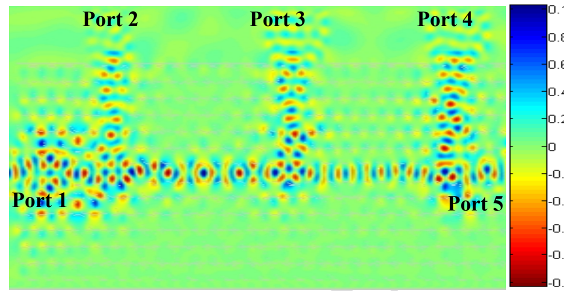

Fig. 2a Snapshot of the electric field when the control beam (ports 2, 3 and4) is ON

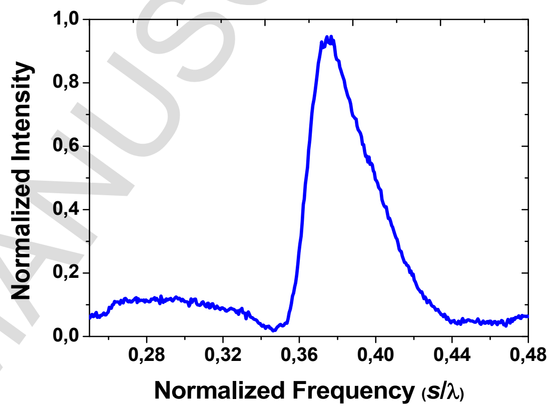

Fig. 2b Light intensity when the control beam is ON (the ports 2, 3 and 4 are ON).

Fig. 2b, shows the light intensity when the signal is injected through ports 2, 3 and 4. The light intensity exhibits a peak in the frequency region from 0.36 s/λ to 0.44 s/λ.

In order to demonstrate the amplification character of the cascaded structure, we inject a signal in port 1, whereas the ports 2, 3 and 4 are switched off. The power flux is shown in figure 3a. It is clear that the propagating signal is attenuated and lost before reaching port 5. The signal is filtered at port 5, in this case, the structure behaviors as an optical filter. To confirm this aspect, we calculate the light intensity; the result is illustrated in figure 3b. The light intensity is about 25% which is in good agreement with the power calculation shown in fig.3a.

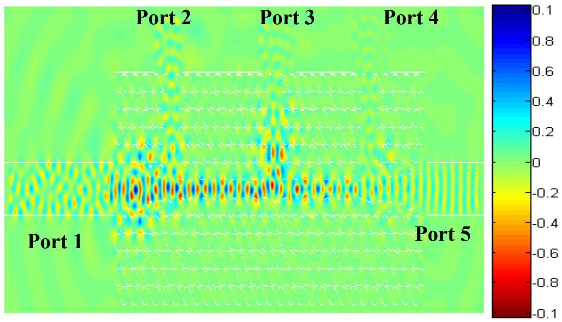

Fig. 3a Snapshot of the electric field when the control beam is OFF (the ports 2, 3 and 4 are OFF)

To have more insight, the light intensity is calculated and reported in figure 3b, it is important to note that the maximum of intensity is less than 25% which agrees with the power flux shown in figure 3a.

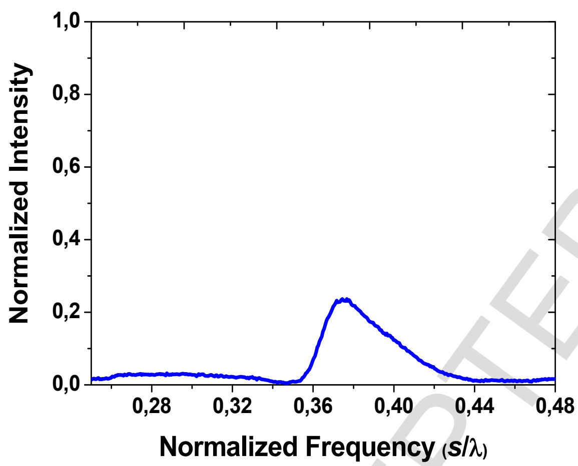

Fig.3b Light intensity when the control beam is OFF (the ports 2, 3 and 4 are OFF)

Next, to demonstrate the light amplification by using only linear effect, the sizes of the defects implemented in the guiding region are modified. We consider three cascade structures separated by a waveguide of length *d*. The cascaded structures are constructed through the juxtaposition of the core building blocks. Each building block is composed of three coupled PCs as described above. The source is placed at port 1 and the control beam (port 2, 3 and 4) are switched from ON to OFF. Firstly, we vary the length *d* of the waveguide to study its effect on the signal amplification and filtering processing. The cascaded structure is depicted in figure 4a.

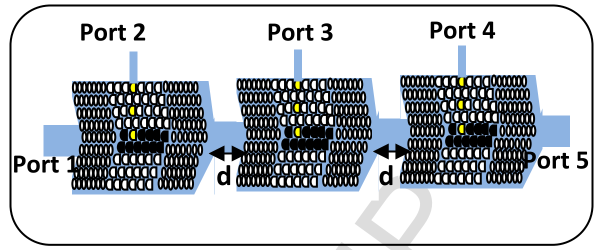

Fig. 4a Schematic of the proposed cascaded structure: The three structures are connected to each other by a guide of length d

We inject a signal in the input port 1, the control ports 2, 3 and 4 are switched ON, the snapshots of the electric field are illustrated in figure 4b when *d* =8s. It is important to note that the power flux propagates and reaches the output port 5. To further confirm this result, we calculate the light intensity for different values of the length, *d* = 6s, *8*s, 11s, the result is illustrated in figure 4c.

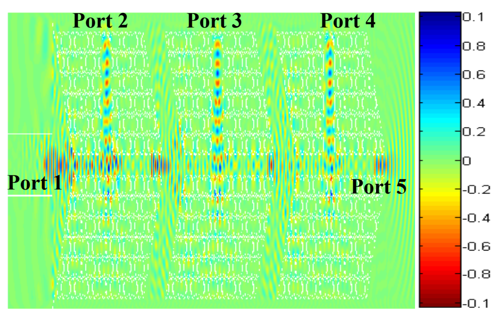

Fig. 4b Snapshot of the electric field when the control beam is ON and d = 8s (the ports 2, 3 and 4 are ON)

The power flux in port 5 as shown in fig.4b, is large could be a sum of signals propagating in ports 1, 2, 3 and 4 because the coupling between these ports is efficient.

It is important to notice that the light intensity of the cascaded structure is about 0.98 when d =8s, and about 0.82 when d = 6s while it drops to 0.68 when d = 11s.

The result of the light intensity is illustrated in figure 4c, it exhibits a peak in the frequency region extending from 0.37s/λ to 0.385s/λ.

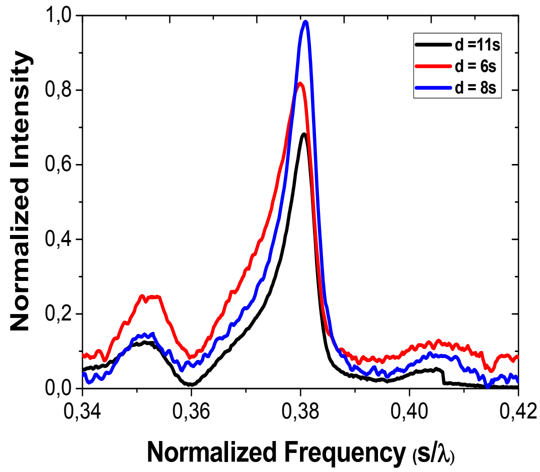

Fig.4c Light intensity versus the frequency for various values of d, when the ports 2, 3 and 4 are switched ON (blue colour *d* = 8s, red colour *d* = 6s and black colour *d*= 11s)

Fig.4c shows that light intensity shifts towards low frequency range as *d* decreases. The simulation shows that when the distance between the structures is *d*=8s, the transmission reaches its maximum 98%. It is worth noting that for this value of *d,* the structure has sufficiently energy to tune and pass with low attenuation reaching the output port 5.

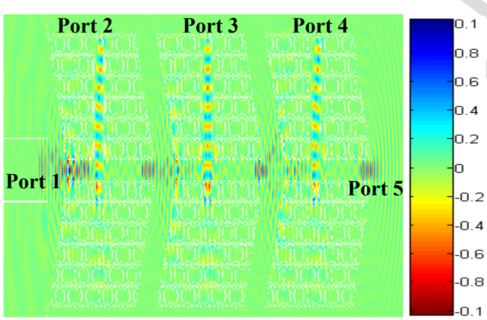

Fig. 5. Snapshot of the electric field when the control beam is ON (the ports 2, 3 and 4 are ON) and *d*= 6s

From figure 5, the snapshot of the electric field reaches port 5. Also, this figure shows the evolution of the electric field in the optimized structure when the ports 2, 3, and 4 are ON. It is clear that the field suffers losses when *d* = 6s.

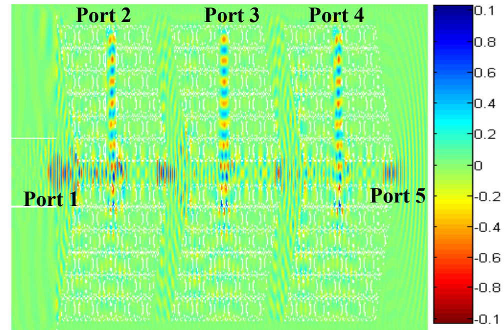

Fig. 6. Snapshot of the electric field when the control beam is ON (the ports 2,3 and 4 are ON) and d= 11s

In order to further confirm the coupling of light between the ports, we calculate the evolution of the electric field in the structure when the separation distance *d* is increased to 11s, it is noticed that the coupling is weak and the intensity is decreased to around 68%. This decrease is related to the loss which is due to the increase of separation distance. The accumulated energy is not high enough to travel from structure block 1 to 3.

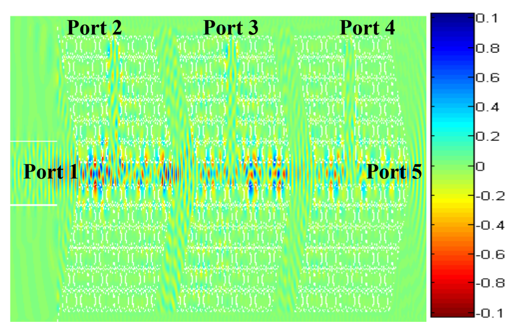

Fig.7. Snapshot of the electric field when the control beam is OFF (the ports 2, 3 and 4 are off) and *d* = 8*a*

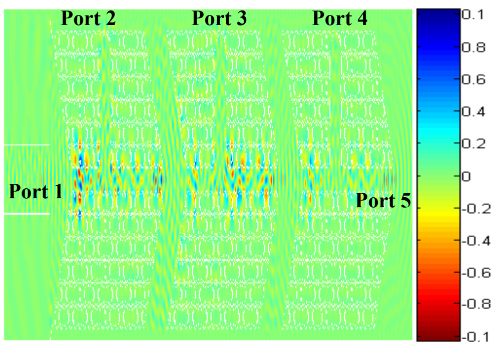

Fig. 8. Snapshot of the electric field when the control beam is OFF (the ports 2, 3 and 4 are off) and *d* = 6s

It is clear from fig.8 that the light is affected and suffers attenuation. The signals in port 1 and ports 2, 3 and 4 are not matched and the coupling is weak.

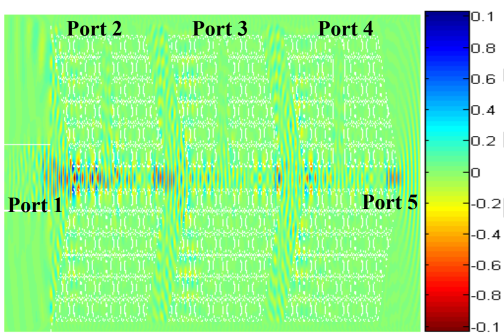

Fig.9 Snapshot of the electric field when the control beam is OFF (the ports 2, 3 and 4 are OFF) and *d*= 11s

The optical signal propagates along the structure and for a coupling length of 11s, the optical losses increase thus the intensity is reduced to 50%. This amount of the signal reaches port 5, in this case the injected light through port 1 is attenuated and about 50 % of the signal is lost.

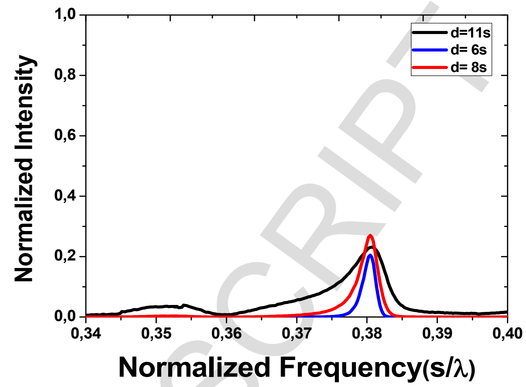

Fig.10.Light intensity when the control beam (ports 2, 3 and 4) are OFF, the length d = 6s, red colour, d = 8s blue colour and d = 11s, black colour.

Figure 10 represents the light intensity when the ports 2, 3 and 4 are off, only the injected signal through port 1 is propagating because no signal is launched in the other ports. The transmitted light intensity is weak for the three distances *d* = 6s, 8s and 11s , the accumulated energy is not high enough in each structure that results in small amount of power to pass through and therefore reaches the output port. It is clear that when no signal is launched in ports 2, 3 and 4, the incident light from port 1 is attenuated and small amount of light intensity about 20% reaches the output port. In this configuration when we cascade three similar structures with ports 2, 3 and 4 are ON, a strong coupling between port1(input) port5 (output) is achieved without nonlinear effects.

Conclusion

We have presented a Si (silicon) based optical amplifier integrated on an ultra-compact platform. The proposed Si amplifier is constructed on a simple linear cascaded photonic structure configuration which demonstrations high amplification efficiency. Our modeling design of this optical amplifier demonstrates significant light intensity amplification. It is shown that the light amplification strongly depend on the cascaded photonic crystal block interconnections, subsequently by coupling the light in the input port (port 1) and control beams in ports 2, 3 and 4 lead to significant increase of the light amplification. It is shown that the geometrical topology of the defects in the guiding region, played fundamental role in the coupling of the light between the cascaded blocks.

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Highlights.

- Optical amplifier integrated on an ultra-compact platform.
- Devices with high optical out power and bandwidth .
- Integration of an amplifier and a filter in a single ultra-compact photonic crystal platform.
- Significant light intensity amplification.
- By cascading three PC building blocks, the peak of the transmission band is strongly influenced.