# 1x3 Beam Splitter Based on Self-Imaging Phenomena in Air-Slab Photonic Crystal Waveguides


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*Abstract*— **A 1x3 beam splitter using multi-mode interference based on self-imaging is demonstrated theoretically and experimentally in PhCWs. The total transmission of the 1x3 splitter is almost equal to the corresponding length of W1 PhCW. The input power is distributed equally between the output ports within 1dB from 1541nm to 1552nm.**



***Keywords- Splitter; Self-imaging; multi-mode interference; Photonic Crystal; Waveguides; e-beam lithography***


## I. Introduction

Beam splitters are central building blocks in large-scale photonic integrated circuits (PICs). There are different ways to equally split the introduced signal into output ports based on photonic crystal waveguides (PhCWs). Some of the most successful structures in PICs are based on slab photonic crystals (PhCs) [1]. In such waveguides, the optical field is confined, horizontally, by a photonic band-gap (PBG) provided by the PhC and, vertically, by total internal reflection due to the refractive index differences between different layers. Various PhCW components can be made by slab PhC, such as bend structures, 1x2 optical beam splitters, including Y- or T-junctions and directional couplers. Most work focuses on single-mode operation in the performance of PhCW. However, multi-mode interference (MMI) in line-defect PhCWs also exhibit extraordinary features [2]. In recent years, there has been a growing trend in the application of MMI effects in integrated optics. The technology for both PhCW and MMI fabrication is well developed.

The wavelength de-multiplexer based on self-imaging phenomena in line-defect PhCWs has been theoretically investigated [3]. TE and TM polarization splitters based on the simulation using self-imaging phenomena in PhCW were studied by Hong *et al.* [4]. Liu *et al.* first investigated theoretically 1x2 splitter based on self-imaging phenomena in line-defect PhCWs [5]. The 2D simulation of Yu *et al.* indicated that the self-imaging phenomena also exist in every other-line defect PhCWs for 1xN (N≥2) splitter [6,7]. The beating length in this every-other-line defect PhCWs is shorter than the conventional coupling length in line-defect PhCWs. Rod slabs were adapted in Liu *et al.*'s research, but high transmittance can only be obtained for very high rods in the slab. High transmittance can be obtained in thin air-slab PhCW, and integration with other building blocks is easily carried out. Standard SOI wafers and e-beam lithography provide our fabrication platform. Here we report the theoretical and experiment result of a 1x3 beam splitter based on self-imaging phenomena in the 340nm top silicon layer of a SOI wafer.

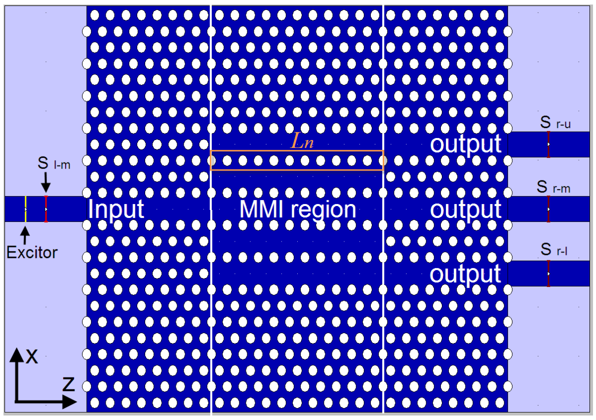


Figure 1. Schematic layout of 1x3 beam splitter consisting of input, MMI and output PhCWs, and excitor and sensors arranged in the ridge waveguides.

## II. Self-Imaging Principle

Bryngdahl *et al.* suggested the possibility of achieving self-imaging in slab waveguides [8], and Urich *et al.* explained the principle in detail [9]. Self-imaging is a property of multi-mode waveguides by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction [2].

The proposed 1x3 beam splitter based on planar PhCW is shown in Fig. 1. It consists of three sections of PhCW, a single-mode input, MMI region with length $L_n$ ($L_n$ needs to be optimized. $n$ is the number of holes and must be an integer) and three single-mode outputs. The lengths of input and output ports were fixed in the theoretical design. The interaction between adjacent output ports can be ignored, due to the separation by three rows of air holes.

## III. Model and Theoretical Simulation

The PhC structure has a pitch of Λ=380 nm in a triangular configuration of air holes with 222nm diameter. This arrangement in silicon (refractive index n=3.476) gives rise to a high transmittance and a band-gap below the silica line for TE-polarized light. The traditional W1 waveguide is obtained by removing a single row of air-holes in the Γ-K direction of the lattice. The in-plane normalized dispersion diagrams for single- and multi-mode PhCWs are shown in Fig. 2. Super-cells are depicted as insets, calculated by 3D plane wave expansion (PWE). It is seen that the frequency range of PhC in both super-cells are similar. One even mode is supported in single-mode PhC, and three even modes are supported in multi-mode PhC. This means that a 1x3 beam splitter is conceivable in this slab design near the frequency of 0.241($\Lambda/\lambda$).

The configuration of Fig. 1 is directly used in 3D FDTD modeling. Different $L_n$'s were simulated (with grid $\Lambda$/24). The calculations show that the component with $L_n$=11$\Lambda$ splits the input equally and exhibits the highest transmittance. This means that the first 3-fold images are obtained around 11$\Lambda$ due to MMI. The net normalized transmittance is obtained by the net transmittance through the sensors in the right ridge waveguides divided by that through the input sensor. The net transmittance for W1 PhCW and the optimized splitter are shown in Fig. 3. From the 3D simulation, the best wavelength is 1567.4 nm and the total normalized transmittance is close to that for a W1 PhCW. The $H_y$ field distribution at 1567.4 nm is depicted in the inset.

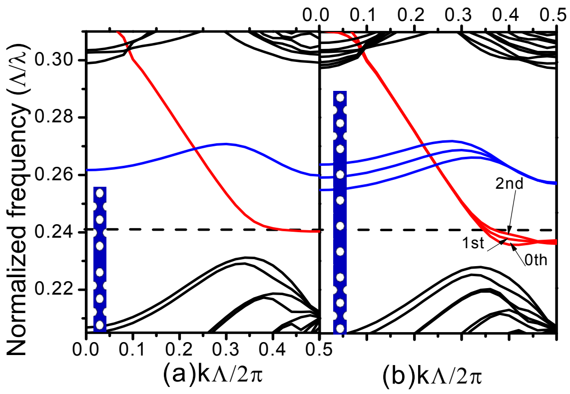


Figure 2. Dispersion diagram for TE polarization of the PhCWs calculated using 3D PWE method. The supercells are shown in the insets. Black lines are PhC modes. Red (blue) line are even (odd) gap-guided modes.

## IV. Fabrication and Characterization

The optimized splitter was fabricated using e-beam lithography and standard anisotropic reactive-ion etching to define the PhCW structure into the 340 nm top silicon layer. A SEM photograph of the optimized splitter is shown as inset in Fig. 4. The air holes have a diameter of 220 +/- 5nm.

The optical properties were characterized by observing the normalized transmittance spectra for TE from 1480 to 1580 nm. The experimental results are shown in Fig. 4. The experimental result is consistent with that of the numerical modeling. The small difference is attributed to the finite gridding, ignoring a few nm native oxide in the modeling and fabrication errors. The total output of the 1x3 splitter is close to the analogue length of W1 PhCW. The power is divided equally into three parts between 1541 and 1552 nm, with the biggest difference among the output ports less than 1dB.

In summary, the numerical and experimental results show that the input beam is split equally into three outputs within a ~ 10nm range near 1550nm. The 1x3 splitter is important for many applications including telecommunications.

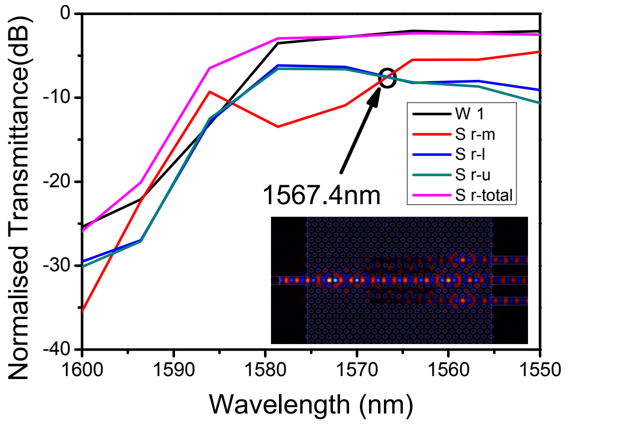


Figure 3. Normalised TE-polarized transmittance (dB) for the splitter with $L_n$=11$\Lambda$, simulated by 3D FDTD. The inset is a snapshot of $H_y$ at 1567.4 nm.

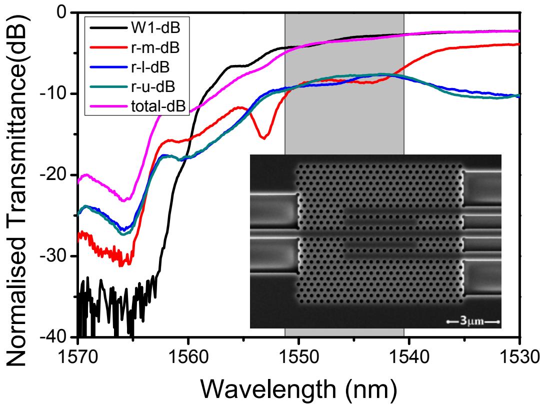


Figure 4. Measured normalised TE-polarized transmittance (dB) for the 1x3 splitter in Fig. 4, the inset is an SEM photograph of the component.

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