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Photonic crystal channel drop filters based on fractal structures

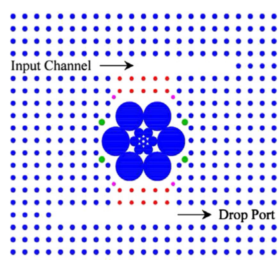
Ali Dideban [a], Hamidreza Habibiyan [a,*], Hassan Ghafoorifard [a,b]

[a] Photonics Engineering Group, Amirkabir University of Technology, 424 Hafez Ave, Tehran, Iran
[b] Department of Electrical Engineering, Amirkabir University of Technology, 424 Hafez Ave, Tehran, Iran

HIGHLIGHTS

- We propose two new configurations of photonic crystal channel drop filters.
- The structures are based on fractal and quasi-fractal shape resonators.
- Drop efficiency and Q-factor of first filter are 95.86% and 1148.95, respectively.
- For other structure, these parameters are 91.70% and 1078.33, respectively.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper we introduce new configurations of channel drop filters based on two-dimensional photonic crystals. Structures consist of two photonic crystal waveguides and a fractal-shaped resonator between them. The effect of structural parameters on resonance frequency and drop efficiency is investigated. Calculations of band structure and propagation of electromagnetic field through devices are done by plane wave expansion (PWE) and finite difference time domain (FDTD) methods, respectively. In our designs more than 95% drop efficiency with quality factor of ~1150 is achievable at wavelength near 1540 nm, which in comparison with other photonic crystal resonator structures is a very satisfactory and acceptable result.

1. Introduction

In the past decade, optical integrated circuits have attained considerable attention for ultra-fast communications and signal processing purposes. Optical channel drop filters (CDFs) are considered as indispensable elements of such circuits due to their high spectral selectivity [1,2]. Conventional technologies employ fiber Bragg grating [3], diffraction grating [4], dielectric thin film [5], arrayed waveguide grating (AWG) [6] and Mach–Zehnder (MZ) interferometers [7], and micro-ring resonator [8], for creating these filters. Among these methods, micro-ring resonator-based CDFs possess a better performance due to higher spectral resolution, widespread tunability, and provision of low channel space [9]. Despite the advantages cited for this configuration; however, there are some drawbacks. Limitations in choosing the ring radius (if the value is less than 5 μm, the propagation losses will increase exponentially), high sensitivity of filter to the distance between ring and bus waveguide, and high sensitivity of structure to the roughness of ring and waveguide surfaces encourages us to use a different configuration in designing the filter [10].

Since 1987, using photonic crystals (PCs) has attracted considerable attention of research communities [11,12]. PCs are artificial periodic lattices with photonic band-gaps which can be used to create different optical elements such as multiplexers, splitters, and CDFs by employing defects in their structures [13–16]. In fact, the potential of such crystals in optical propagation, confinement in small scale, flexible design and excellent performance have caused a growing interest in their addition to semiconductor devices [17,18].

* Corresponding author.
E-mail address: habibiyan@aut.ac.ir (H. Habibiyan).

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In the past decade, most research works on PC-based CDFs have been carried out in the two-dimensional (2D) PC systems, due to their relative ease of fabrication by using the state-of-the-art microfabrication technologies. Akahane et al. introduced a surface-emitting design consisting of a waveguide and cavity [19]. In their structure, an input light entered the waveguide, tunneled through the cavity via the drop wavelength, and eventually left the cavity vertically. In this configuration, it is typically not possible to receive the emitted light from below the structure and thus in the best conditions 50% drop efficiency can be achieved [20]. Fan et al. investigated a four-port CDF with a resonator based on PCs [21]. The results indicated that the complete signal dropping from a waveguide to another parallel waveguide materialized when the resonator between the two waveguides supported two degenerate resonance modes with different symmetries. Rostami et al. designed an L4 cavity demultiplexer in modified-T photonic crystal structure. The cavity was formed in the Si slab after removing four pores, and the drop wavelength was adjusted by changing the size and place of cavity margins [22]. Their simulations indicated that the average crosstalk between adjacent channels and the average quality factor (Q, defined as the ratio of the center wavelength to line width of drop channel, where, line width is signal width at the half of its maximum) were −21.1 dB and 3488, respectively. In another study, Ren et al. presented a PC-CDF with wavelength-selective reflection micro-cavity consisting of two micro-cavities [23]. One of the cavities was used to tunnel through the drop port while the other performed wavelength-selective reflection feedback in the waveguide bus so that the first cavity reached the maximum drop efficiency. Kumar et al. investigated the coupling between waveguides and a PC-based ring resonator [24]. Their results illustrated that ring dimensions and crystal parameters have a significant effect on resonance behavior of resonator. Bai et al. presented a new 45°PC-ring resonator (PCRR) based on square lattice of silicon rods [10]. They obtained 90% drop efficiency and Q factor of more than 830. Recently different structures, such as X-shaped and elliptical resonators, have been proposed for optical CDFs, instead of conventional rings [25,26]. Drop efficiencies of these filters have been reported close to 100% with Q factors of 196 and 647, respectively.

Many experimental results of CDFs that are built in the 2D PC platforms have been reported [18], [27–37]. Noda et al. proposed the surface-emitting three-port CDF, which consists of a cavity side coupled to a waveguide. The signal dropped from the bus channel to the cavity then emits to free space and can be collected [27]. The concept of in-plane hetero-photonic crystals, which consist of a series of connected PC regions with different lattice constants, has been proposed by Noda's group [28]. In another work, Akahane et al. reported a theoretical and experimental study of a CDF with two cascaded point-defects between two line-defects in a 2D PC slab. Furthermore, they theoretically demonstrated that drop efficiency was increased dramatically, up to 93%, by introducing hetero-photonic crystals with different lattice constants. One of the PCs served as a wavelength-based mirror, while the other one dropped a larger amount of optimal wavelength [30]. Hetero-photonic crystal structures have been used to demonstrate high quality factor (more than 1 million) wavelength drop operations [31,32]. Also, higher-order resonant modes for a heterostructure nanocavity formed in a 2D PC silicon slab have been considered [33]. Using the concept of heterostructure photonic crystals, a four-channel demultiplexer has been experimentally investigated by Takano et al. [34]. The device consists of four simply connected filter units with 5 nm lattice constant differences. The reported channel spacing is about 20–24 nm. In the proposed structure, the authors used bent waveguides as drop waveguides, and then the device size is large. In another work, Shinya et al. experimentally demonstrated an ultrasmall five-channel demultiplexer [35]. The dropped signals have wavelength separation of about 30 nm in CL-band.

Compared to the profound and systematic theoretical and experimental studies on 2D PC CDFs, research works on three-dimensional (3D) PC CDFs are much fewer and less extensive. The major reason can be related to the difficulties and challenges to fabricate 3D PC devices in the optical wavelengths. Among all the 3D PC platforms, the woodpile structure has attracted considerable interest in the context of CDFs [38–41] because the structure has less fabrication problems. In spite of many theoretical and experimental works reported on this structure, creation of various linear waveguides and localized cavities and their coupling remains a topic for extensive investigation. Bayindir et al. experimentally investigated a surface-emitting CDF in the microwave regime [39]. Kohli et al. experimentally and theoretically demonstrated a special CDF in the 3D woodpile PC that required 4 stacked layers between the waveguides and defects, which is difficult to realize at optical/infrared wavelengths [40]. In another work, Stieler et al. developed an efficient 4-port planar CDF where the entire filter resides in a single layer of the 3D PC, thus fabrication at optical length scales is simplified [41].

In this paper, we attempt to introduce new configurations of photonic crystal CDFs based on fractal resonators. Being fractal here refers to patterns that reiterate continuously within themselves in smaller scales. Two structures, each comprising of a fractal resonator and two parallel PC waveguides, are introduced. In the drop wavelength, light tunnels from bus waveguides to resonators. Having resonated there, it ultimately moves to the drop waveguides.

The remainder of this paper is organized as follows. In Section 2, the first structure and its effective parameters are introduced. In Section 3, the optimum values of structural parameters and simulation results are presented. In Section 4, the second structure and its behavior are studied. Finally, a brief summary of the work is given in Section 5.

2. The first proposed structure

In this paper we focus on the PC structures with square lattice of dielectric rods. However, we expect that the trends proposed here will apply to other type of 2D PCs, such as air hole structures. In our design, a two-dimensional PC consisting of 23 × 21 dielectric rods in square lattice surrounded in air ($n_l = 1$) has been used. The lattice constant, rods radii, and their refractive index are $a = 520$ nm (for operating at the wavelength of ∼1550 nm), $r = 0.22a = 115$ nm (the best filling ratio for providing the widest photonic band-gap), and $n_h = 3.4$ (related to GaAs at 1550 nm), respectively.

According to the band structure, obtained by 2D-PWE method, there is a band-gap for TM modes in the normalized frequency range of 0.271–0.394 (a/λ), or the wavelength range of 1319.79–1918.82 (nm). In fact, light with TM polarization will not be allowed to propagate in the PC within the aforementioned ranges. If we remove a row of rods from this lattice; hence causing a line defect, we have a PC W1 waveguide. In this waveguide, the complete

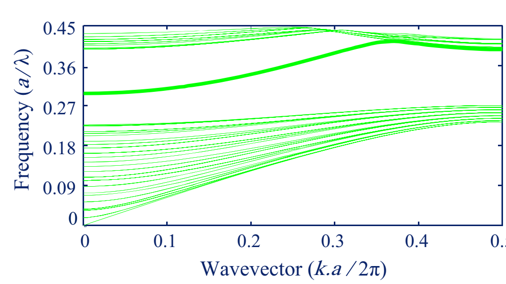

Fig. 1. Dispersion curve of W1 bus waveguide.