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# Full-optical tunable add/drop filter based on nonlinear photonic crystal ring resonators

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**Abstract**

Here, we propose a full-optical tunable Add/Drop filter based on single (SR) and double-vertically (DR) aligned Kerr-like nonlinear photonic crystal ring resonators (PCRRs). Silicon (Si) nano-crystal is used as the nonlinear material inside and outside of PCRRs. The minimum optical power required to turn–on/turn–off the SR and DR filters are 2000 mW/μm$^2$, and 150 mW/μm$^2$, respectively. We believe since the DR filter has a higher $Q$-factor rather than SR and also since the optical power reads more nonlinear rods with a longer time to pass the structure, thus the optical power required is much lower (10 folds). In addition, the minimum power required to 1 nm redshift the center operating wavelength of SR filter is 125 mW/μm$^2$ (i.e. $\Delta n_{NL} = 0.005$) and for DR is as low as 8 mW/μm$^2$. Performance of the Add/Drop filter structure is simulated by means of finite difference time domain (FDTD) method, in which the simulations showed an ultra-compact size structure with promising ultrafast tune-ability speeds.


*Keywords:* Tune-able add/drop filter; Photonic crystal; Ring resonator; Nonlinear; Optical Kerr effect

## 1. Introduction

In the past decade, Photonic crystal (PhC) cavities and ring resonators have attracted increasing attention for their ability to sustain very high Q-factors and low mode volumes, resulting the optical integrated circuits (OICs) become ultra-compact sized [1,2]. Due to their low response and recovery time (lower than a few picoseconds) [3,4], ultrafast switching applications are simply realized. They require only a few microwatts of power to demonstrate appropriate nonlinear effects, and furthermore, due to Si-based technology of PhCs, complex fabrication processes are easily derived [5]. Through periodic arrangements of these optical materials, an enormous number of artificial structures are born that have immensely helped the scientific community to observe and experimentally study a broad range of optical phenomena such as Kerr-like third order susceptibility [6], two-photon-absorption [7], negative refraction [8], optical memory and light storing [9], Optical whispering gallery modes for ultra-high $Q$-factors [10] and even in Terahertz domain for pulse propagation and wave-guiding [11,12], pulse detection [13] and pulse wave generation [14].

In optical realm and specifically for 2DPhCs, various methods have been proposed for applying tuning

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abilities and controlling the properties of the desired devices, however the approaches used so far suffer from several disadvantages. For example, application of thermo-optic methods in a 2DPhC switch [15,16] showed a switching speed in the μs order that is not very likely for ultrafast speed needs. Furthermore, application of electro-optic technique are reported in [17–19], but the applied voltage limits the operating speed. Directional coupler structures reported in [20,21], suffer from their large coupling lengths resulting in consumption of larger amounts of optical powers. On the other hand, nonlinear optical processes have shown amazingly ultrafast responses on the order of 10 ps [22,23]. These phenomenon is believed to exist due to either the strong nonradiative recombination of the photo-carriers at etched holes [22], and to the carrier induced nonlinear index fast wavelength shifting of a PhC resonance [23].

Considering all these point outs, and combining them with ultrafast speeds, ultra-compactness and extremely low power consumption and loss levels of 2DPhCs, here in this paper we propose two Kerr-like nonlinear full-optical Add/Drop tune-able blocks capable of complete on/off operating at threshold input intensities as low as 2000 mW/μm$^2$ for a single ring (SR) PhC ring resonators (PCRR) and 150 mW/μm$^2$ for a double-vertical (DR) aligned PCRRs. Our proposed SR and DR structures are sandwiched between two parallel W1 line defect waveguides. For empowering these nonlinear blocks to function at such low level input intensities, silicon (Si) nanocrystal is used inside of both PCRRs as the nonlinear material [24,25]. Performance of the structure is simulated by means of finite difference time domain (FDTD) method that is known to be an effective method for analysis of PhC structures. FDTD provides EM field variations in space with respect to time and fully approximate Maxwell's curl equations of a real space if appropriate boundary conditions are applied [26–28]. We believe that modern advances in micromachining and planar technology, could easily enable us to integrate our proposed all-optical Add/drop structure into an optical microchip suitable for DWDM systems operating at telecommunication center wavelength of $\lambda_0 = 1550$ nm.

The organization of the paper is as follows: in Section 2, we present the modeling of the proposed tunable add/dropping structures based on nonlinear PhC ring resonators. We establish our numerical results in Section 3 and finally in Section 4, we close this paper with concluding remarks.

## 2. Numerical methods and modeling

Ring and cavity resonators are used to enhance nonlinear effects in optical applications. The light trapped inside a ring propagates in a circular closed path and since it continuously circulates, under the self-consistency condition (self-reproducing of field distributions and phase of light in each resonator round trip) it modes can constructively interfere with each other and form a standing-wave pattern [29–31]. This continuously circulations of light inside the resonator coherently builds up its intensity to higher levels (even higher than that incident upon the resonator) and enhance the optical power and therefore a strong AC Kerr effect is achieved. For simplicity, we neglect the material and chromatic dispersion effects and assume that the fields are linearly polarized, thus total polarization due to second and third order nonlinearities are given by [32]:

$$\vec{P}_x = \varepsilon_0 \left[1 + \chi^{(1)} \cdot \vec{E}_x + \chi^{(2)} \vec{E}_x \cdot \vec{E}_x + \chi^{(3)} \left|\vec{E}_x\right|^2 \cdot \vec{E}_x\right] \tag{1}$$

where $n_L{}^2 = \varepsilon_L = 1 + \chi^{(1)}$ is the dielectric constant. Here $\chi^{(2)}$ and $\chi^{(3)}$ are second order and third order nonlinear susceptibilities. At a single frequency of $\omega$, only the cubic nonlinearity; i.e. Kerr effect, is associated with oscillating part of the polarization that is found to be [27,33]:

$$P_{NL} = \frac{3}{8} \varepsilon_0 \chi^{(3)} |E_0|^2 E_0 e^{-i\omega t} \hat{x} \tag{2}$$

The self-consistency condition (for instructive interference) applies only after a full resonator round trip only when total optical phase shift is equal to an integer multiple of 2π, thus for a certain length of resonator, only a few optical frequencies can resonance and light only for this frequencies can goes off. Combination of these rings and cavities with conventional wave guiding means such as $W_1$ line defect waveguides in PhC structures, form different types of optical devices. Fig. 1 shows two of common archetypes of these devices. In linear regime, Fig. 1a is known to acts as a backward optical Add/Drop filter and Fig. 1b, two vertically-aligned rings are coupled with two bus waveguides to form a forward add/drop filtering device [34]. However, in nonlinear regime both of Fig. 1a and b can be used a building block of optical switches [16], logic gates [6], optical limiters [35] and even an successive approximation based analog to digital converter [36]. In this cases the round-trip phase shift depends on the field intensity of the resonating mode.