Coupled micro-ring resonator based optical en/decoder for 2-D coherent OCDMA application

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ABSTRACT
We propose a novel reconfigurable optical encoder/decoder for two-dimensional (2-D) coherent OCDMA application. The proposed device is based on the reflective characteristic of cascaded coupled double micro-ring resonators. The ring-ring and ring-bus coupling coefficients have been optimized to achieve a flat-top reflective spectrum by using transfer-matrix method. Numerical analysis indicates that the proposed device enables simultaneous tuning of the wavelength hopping and spectral phase encoding patterns.
Keywords: Optical code division multiple access (OCDMA), integrated optics, optical encoder/decoder, micro-ring resonator

1. INTRODUCTION

Optical code division multiple access (OCDMA) technique has attracted intensive research over the past decade, mainly due to its unique advantages of high speed all-optical signal processing, fully asynchronous transmission with low latency access, simplified network management, potentially improved security and so on [1-2]. The OCDMA system can be classified into incoherent or coherent OCDMA according to the operation principle, or according to the working dimensions as one dimensional (1-D), or two-dimensional (2-D) OCDMA [2]. Among the various components in OCDMA system, the optical encoder/decoder is the key device that will greatly limit the system performance. Fiber optical delay line (FODL), planar lightwave circuits (PLC), spatial light modulator (SLM), fiber Bragg gratings (FBG) and micro-ring resonator (MRR) [4-8] have been used for either 1-D or 2-D OCDMA en/decoding. A time domain spectral phase en/decoding scheme using an array of FBG and high-speed phase modulator for 2-D coherent en/decoding has also been demonstrated [9].

In this paper, we propose a novel optical encoder/decoder based on coupled double micro-ring resonator for 2-D coherent OCDMA application. The proposed device is ultra-compact, integrated and programmable. Moreover, due to the reflective characteristic, it exhibits the unique capability of simultaneous reconfigurable fast wavelength hopping and spectral phase encoding using only single device that are not have for previous optical en/decoders.

2. PROPOSED OPTICAL EN/DECODER

Figure 1 shows the configuration of the proposed device, which consists of several pairs of identical coupled double micro-ring resonators. In this paper, four pairs are used as an example. Each pair is composed of two weakly coupled-ring resonators that are both coupled with a bus optical waveguide. A heater is laid over every single ring resonator to change the effective refractive index by using thermal-optic effect to tune the resonant wavelength. Electro-optic effect can also be applied to enable high speed tuning. A phase shifter (PS) is placed on the bus waveguide between two adjacent pairs of coupled resonators to adjust the relative phase shift of the reflected spectral component according to a unique optical code, which can be "π" for code "-1", or "0" for code "1". The interval between two pairs is L corresponding to time delay T=2nL/c, where c is the light velocity, n is the effective refractive index. T is chip duration of the optical code.

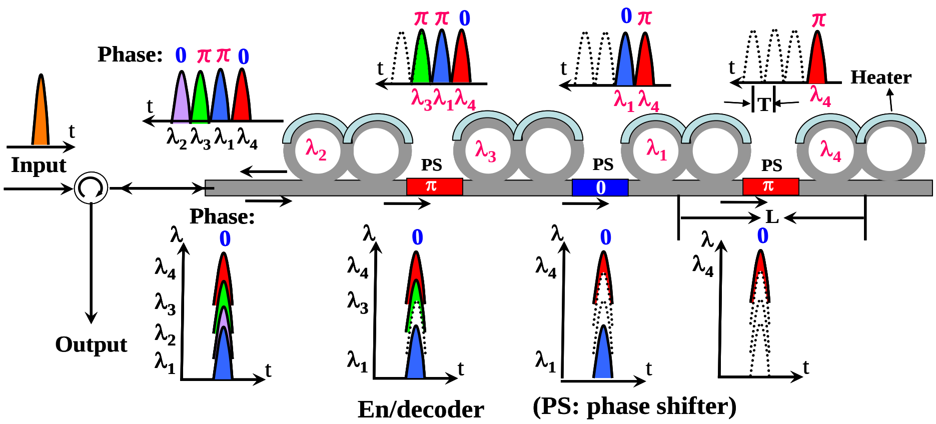

Fig.1 Schematic diagram of proposed optical en/decoder based on coupled micro-ring resonators

The working principle of this device is illustrated in Fig. 1. The 2-D coherent optical code to be generated is shown in Fig.2 (a). The wavelength hopping code (WHC) is (λ_2, λ_3, λ_1, λ_4) and the spectral phase code (SPC) is (0ππ0). An ultra-short optical pulse with a broadband spectrum is firstly coupled into the bus waveguide. By properly tuning the resonant wavelength of the first pair of coupled resonators, the spectral component of λ_2 is on resonance. λ_2 is therefore reflected back and output from the waveguide, while the other off resonance wavelength (λ_1, λ_3, λ_4) will transmit through the structure. Similarly, the spectral component of λ_3 is reflected back from the second pair of coupled resonators after experiencing a relative time delay T and has π relative phase shift (π) adjusted by the first PS. The remaining spectral components of λ_1, λ_4 ... are operated in the same manner by the rest resonators and the output optical signal from the waveguide is encoded by the 2-D optical code. Both the WHC and SPC can be reconfigured simultaneously by the heaters and PSs, respectively. The decoder has the same structure but is used in the reverse order.

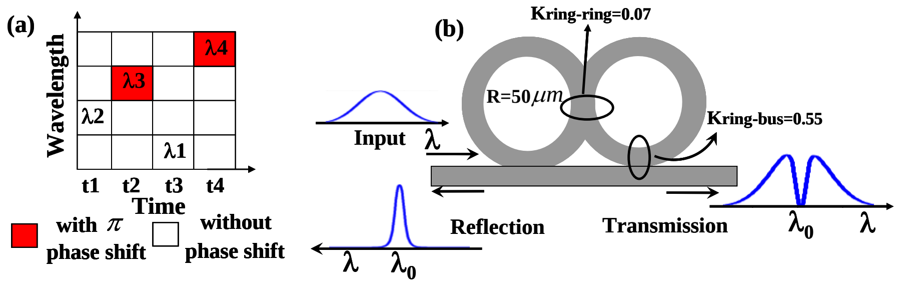

Fig.2 (a) Wavelength hopping code (WHC) and spectral phase code (SPC) map and (b) configuration of coupled double micro-ring resonator (one frequency bin)

To reduce the cross-talk between two adjacent frequency bins and effectively improve the decoding performance, a box-like flat-top reflective spectral response is highly desirable for the proposed device. Figure 3 (a) and (b) show the peak intensity and 3dB bandwidth of the reflective spectrum versus the ring-bus and ring-ring coupling coefficient, respectively. The coupling coefficients between the ring-ring and ring-bus are illustrated in Fig.2 (b). As shown in Fig.3 (a), the peak reflectivity gradually decreases as the ring-bus coupling coefficient $k_{ring\text{-}bus}$ increase from 0.5, while the 3dB bandwidth gradually increases with the $k_{ring\text{-}bus}$. The reflective spectrum will split into multiple peaks if $k_{ring\text{-}bus}$ is less than 0.5. When $k_{ring\text{-}bus}$ is equal to 0.5, the peak reflectivity and the 3dB bandwidth will both increase with the ring-ring coupling coefficient $k_{ring\text{-}ring}$ until 0.08. Further increase of the $k_{ring\text{-}ring}$ will also induce splitting of reflective spectrum. A nearly flat-top spectral response with high reflectivity can be obtained as the $k_{ring\text{-}bus}$ and $k_{ring\text{-}ring}$ vary between 0.5~0.6 and 0.06~0.08, respectively.

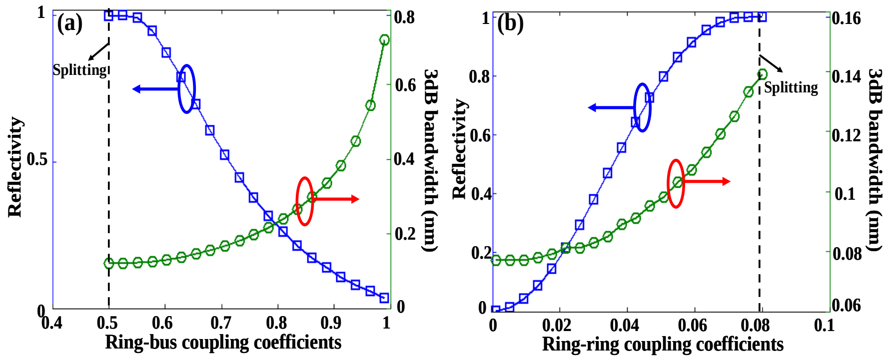

Fig. 3 Reflectivity and 3dB bandwidth versus: (a) $k_{ring\text{-}bus}$ and (b) $k_{ring\text{-}ring}$

3. ENCODING/DECODING PERFROMANCE

The encoding and decoding performance have been simulated by using a Gaussian-shaped optical pulse with pulse width of ~1.6ps. The ring resonator has a radius of 50μm, and the coupling coefficient of $k_{ring\text{-}bus}$ and $k_{ring\text{-}ring}$ are chosen as 0.55 and 0.07 to achieve a 3dB bandwidth of 0.12nm for each frequency bin. The chip rate is set as 20GHz/chip corresponding to chip duration of 50ps for L=2.5mm and n=3. Figure 4 (a) and (b) shows the encoded waveform for wavelength hopping code of {1, 2, 4, 3} and {1, 4, 3, 2} with spectral phase pattern {0, 0, 0, 0}, from which one find that the sequence of the wavelength λ_1, λ_2, λ_3 and λ_4 can be hopped according to the WHC.

The simultaneous wavelength hopping and spectral phase encoding is also verified by applying a spectral phase code {1, -1, 1, -1} for WHC {2, 3, 1, 4}, as shown in Figure 5 (a). To effectively recover the original optical pulse, both the WHC and SPC are indispensible in the decoder. Fig. 5 (b-i) depicts the auto-correlation

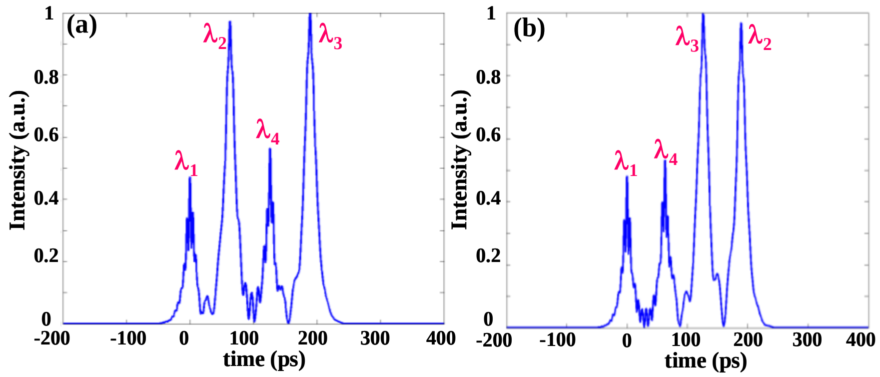

Fig. 4 Encoded waveform for wavelength hopping code: (a) {1, 2, 4, 3} and (b) {1, 4, 3, 2}

signal with high peak power and needle pulse, while for the incorrect SPC (ii) and incorrect WHC (iii), the decoded optical waveforms still spread in time domain, which verifies the feasibility of 2-D coherent en/decoding using the proposed device. By adopting more frequency bins, the power contrast ratio between the auto-/cross-correlation can be further improved and the code space size can be increased correspondingly, which may enhance the capacity and security of the OCDMA system.

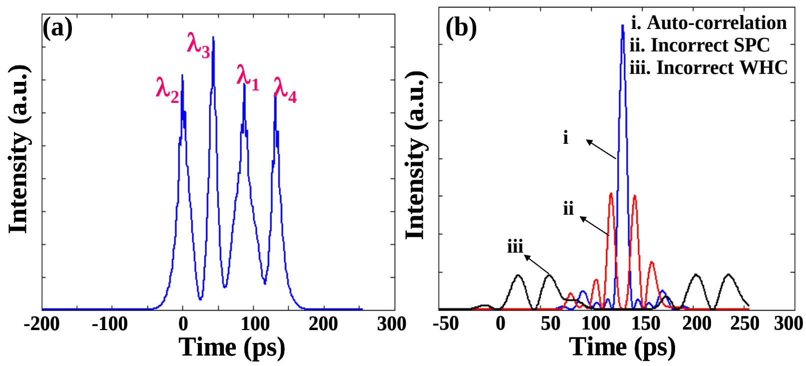

Fig. 5 (a) Encoded waveform for WHC {2, 3, 1, 4} and SPC {1, -1, 1, -1}; (b) Decoded waveform for: (i) correct WHC and SPC; (ii) incorrect SPC and (iii) incorrect WHC

4. CONCLUSIONS

A novel optical encoder/decoder composed of double coupled micro-ring resonators is proposed for two-dimensional coherent OCDMA application. By optimizing the coupling coefficients of rings-bus waveguide and ring-ring resonator, a box-like reflective spectral response can be formed for each frequency bin. The coding performance of reconfigurable wavelength hopping and spectral phase encoding has been investigated by simulation. The proposed micro-ring resonator based optical encoder/decoder can be integrated with other photonic devices, enabling an ultra-compact, flexible and programmable 2-D coherent OCDMA system.

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