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A scheme to expand the delay-bandwidth product in the resonator-based delay lines by optical OFDM technique

Jiangbo Zhu [a,*], Li Tao [a], Ziran Zhang [a], Minhao Pu [b], Haiyan Ou [b], Nan Chi [a], Siyuan Yu [c]

[a] State Key Lab of ASIC & System and Department of Communication Science and Engineering, Fudan University, Shanghai 200433, China
[b] Department of Communications, Optics & Materials, Building 345V, NanozDTU, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[c] Photonics Group, University of Bristol, Bristol, United Kingdom

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ABSTRACT

We propose a novel scheme to expand the inherent limit in the product of the optical delay and the transmission bandwidth in resonator-based delay lines, with the optical orthogonal frequency division multiplexing (OOFDM) technique. The optical group delay properties of a single ring resonator were theoretically studied, and double-carrier OOFDM signals were transmitted through such a device in the experiment, where the subcarrier-frequencies matched those of the resonant modes in the device. The results show that, although the delay-bandwidth product (DBP) is limited in the order of 50 ps × 10 Gb/s for signals on each of the sub-carriers, the total DBP of the system is doubled to 2 × 50 ps × 10 Gb/s due to the double-carrier transmission.

1. Introduction

When light travels in some medium with a group velocity v_g much lower than the vacuum velocity c, stronger light-matter interaction is promoted, and delay or even temporarily store of light can be realized. Hence, "slow" light has attracted much attention over the last decade since it is prospective for a wide range of applications, including nonlinear optics [1], sensing [2], as well as all-optical buffer and memory [3].

As to the application of delay lines for information technologies, optical devices based on structural resonance have been extensively studied [4–6], since they have greater flexibility in operation wavelengths and bandwidths compared with slow light devices based on the intrinsic optical properties of material systems [7]. However, resonator-based delay lines are highly structural dispersive only around each of their resonant frequencies [6], resulting in a trade-off between the optical delay and the transmission bandwidth available in these devices: the group delay of light signals transmitted will decrease as the data rate increases. This fundamental limitation is also referred to as a figure of merit called delay-bandwidth product (DBP) [8], which approximately measures the delaying capacity of a slow light device [9].

Since a qualified optical delay line is required to provide large delay as well as wide transmission bandwidth, several approaches have been proposed to address this problem. Two main schemes are to employ coupled-resonator optical waveguides (CROWs) [10] or photonic crystals (PhCs) [11], which both consists of periodic resonance structures. CROWs- and PhCs-based delay lines have been demonstrated with effectively improved DBP performance compared with single-resonator components, as well as tunability of the delay time with proper manipulation [12]. Nevertheless, the inevitable disorder and imperfections in these devices, and a finite quality-factor (Q) caused by all kinds of loss mechanisms will still limit the DBP increase to a higher degree [13].

In an earlier paper, we proposed a novel scheme to expand the DBP of resonator-based delay lines by employing the optical orthogonal frequency division multiplexing (OOFDM) technique [14]. OFDM technique was developed several decades ago and has become the basis of many communication systems, including both wireless and wired applications [15]. In recent years, OOFDM has been studied extensively as a competitive technique for the next generation high-speed long-haul fiber transmission systems [16,17]. Applying the multi-subcarrier transmission of an OOFDM system to a single optical multi-modes resonator, with the subcarrier-frequencies chosen to match those of the resonant modes, the effective transmission bandwidth is expected to be multiplied by the number of the subcarriers used. Thus, the effective DBP will be multiplied by the same factor. In this paper, we experimentally achieve to setup a two-subcarrier OOFDM system, and the OOFDM signals are transmitted through a silicon-based four-port ring resonator (FPRR). The total DBP of

* Corresponding author. Tel.: +86 21 65643297.
E-mail address: zjb227@gmail.com (J. Zhu).

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the entire system is proven to be twice the DBP of single-carrier transmission, verifying the viability of this scheme.

In Section 2, we build a theoretical model of FPRR circuits, and analyze the group delay and insertion loss properties of the device used in our experiment. In Section 3, the experimental results are given to demonstrate the feasibility of our approach. Section 4 concludes the paper with a summary of our results and discussions.

2. Modeling for FPRR circuits

In order to investigate the fundamental group delay properties of ring resonators, we develop a generalized model of FPRR circuits. In an earlier research of Uranus et al., two-port ring resonators (TPRRs) are profoundly studied. TPRRs will operate in four v_g regimes under different combination of coupling and attenuation coefficients, including “fast” and “slow” light regimes with positive and negative group indices [6]. To use a TPRR as an optical delay component, which shall “slow” the light with large positive group index, requires the precise control on the coefficients.

Instead of TPRRs, we use a FPRR as the delay component. A typical FPRR consists of a ring resonator and two straight access waveguides, as shown in Fig. 1. We assume that both the ring resonator and the access waveguides are single-mode waveguides. When the light is launched into the FPRR at the input port, assuming the time dependence of $\exp(i\omega t)$, the transfer functions of the access waveguide sections can be written as

$$S_i = \exp(-i\beta_{awg}L_i - \alpha_{awg}L_i) \quad i = 1,\ 2,\ 3 \tag{1}$$

where $S_1 \equiv b/a$, $S_2 \equiv f/d$, and $S_3 \equiv n/m$; variables a to n represent the light fields at corresponding positions in Fig. 1; β_{awg} and α_{awg} are the propagation constant and the attenuation constant of the mode in the access waveguides, respectively; L_1, L_2, and L_3 are the length of waveguide sections where no coupling with the ring resonator occurs, as illustrated in Fig. 1.

Then we describe the coupling region between the waveguide AC and the resonator by the scattering matrix [5]

$$\begin{bmatrix} c \\ e \end{bmatrix} = P \begin{bmatrix} b \\ d \end{bmatrix}, \quad P \equiv \frac{1}{\kappa} \begin{bmatrix} -\tau & 1 \\ -1 & \tau \end{bmatrix} \tag{2}$$

where τ is the transmission coefficient, and κ is the dimensionless coupling coefficient over the coupling length. Using the classic coupled-mode theory (CMT) analysis [18], τ can be taken as a purely real number and κ as a purely imaginary number for a lossless directional coupler, and $|\tau|^2 + |\kappa|^2 = \tau^2 - \kappa^2 = 1$.

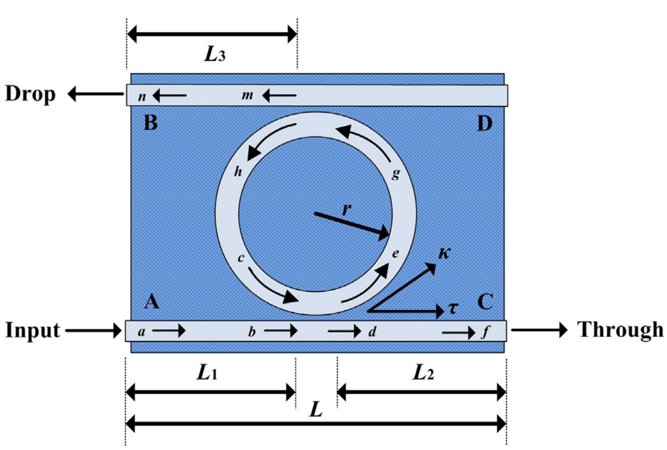

Fig. 1. Schematic diagram of a FPRR circuit and the notations used in the analysis.

The transfer functions of the ring resonator are

$$\begin{bmatrix} g \\ h \end{bmatrix} = Q \begin{bmatrix} c \\ e \end{bmatrix}, \quad Q \equiv \begin{bmatrix} 0 & \exp(-i\pi r\beta) \\ \exp(i\pi r\beta) & 0 \end{bmatrix} \tag{3}$$

and

$$R \equiv \frac{c}{e} = \exp(-i2\pi r\beta) \tag{4}$$

where $\beta = \beta_{res} - i\alpha_{res}$, while β_{res} and α_{res} are the propagation constant and the attenuation constant of the mode in the resonator, respectively; r is the effective radius of the resonator. We assume the coupling between the waveguide BD and the resonator being same with that between the waveguide AC and the resonator, and then we have

$$\begin{bmatrix} 0 \\ m \end{bmatrix} = P \begin{bmatrix} g \\ h \end{bmatrix} = PQ \begin{bmatrix} c \\ e \end{bmatrix} = PQP \begin{bmatrix} b \\ d \end{bmatrix} \tag{5}$$

Using Eq. (2) to Eq. (5), we can obtain the transfer functions of the drop port and through port of the FPRR circuit

$$T_D \equiv \frac{n}{a} = \frac{b}{a}\frac{m}{b}\frac{n}{m} = \exp(-i\beta_{awg}L - \alpha_{awg}L)\frac{(\tau^2 - 1)\sqrt{\gamma}\exp(-i(\theta/2))}{1 - \tau^2\gamma\exp(-i\theta)} \tag{6a}$$

$$T_T \equiv \frac{f}{a} = \frac{b}{a}\frac{d}{b}\frac{f}{d} = \exp(-i\beta_{awg}L - \alpha_{awg}L)\frac{\tau - \tau\gamma\exp(-i\theta)}{1 - \tau^2\gamma\exp(-i\theta)} \tag{6b}$$

where $\gamma = \exp(-2\pi r\alpha_{res})$ and $\theta = 2\pi r\beta_{res}$ are the round-trip transmission and phase change coefficients, and we also assume $L_1 + L_2 = L_1 + L_3 = L$. Then the insertion losses and effective phase shifts from the two ports of the FPRR circuit are defined as

$$L_D = -20\log|T_D|, \quad L_T = -20\log|T_T| \tag{7}$$

$$\phi_{eff,D} = -\arctan\frac{\mathrm{Im}(T_D)}{\mathrm{Re}(T_D)} + 2\pi p, \quad \phi_{eff,T} = -\arctan\frac{\mathrm{Im}(T_T)}{\mathrm{Re}(T_T)} + 2\pi p \tag{8}$$

where p is an arbitrary integer and can be neglected in the following analysis. Thus, the group indices, which indicate the group delay performance, can be written as

$$n_{g,D} = \frac{c}{v_{g,D}} = n_{awg} + \frac{\pi r n_{res}}{L}\frac{1 - \tau^4\gamma^2}{1 + \tau^4\gamma^2 - 2\tau^2\gamma\cos\theta} \tag{9a}$$

$$n_{g,T} = \frac{c}{v_{g,T}} = n_{awg} + \frac{2\pi r n_{res}}{L}\frac{(1 - \tau^2)\gamma((1 + \tau^2)\gamma - (1 + \tau^2\gamma^2)\cos\theta)}{(1 + \tau^2\gamma^2)^2 + \gamma^2(1 + \tau^4 + 2\tau^2\cos 2\theta) - 2\gamma(1 + \tau^2\gamma^2)(1 + \tau^2)\cos\theta} \tag{9b}$$

where group velocity is defined as $v_g = \partial\omega/\partial\beta_{eff} = L\partial\omega/\partial\phi_{eff}$ [19]; n_{awg} and n_{res} are the effective indices of the mode traveling in the access waveguide and the resonator, respectively; meanwhile, we assume that the attenuation constant, the coupling constant, and the effective indices are independent of frequency.

In the following calculation, we consider a FPRR with r, L, n_{awg}, and n_{res} of 600 μm, 10 mm, 2, and 2, respectively. In this paper, only positive τ will be considered, since negative τ will give the same results [6].

First, at the resonance condition ($\theta = 2\pi r\beta_{res} = 2\pi q$, q is an integer), the group indices and insertion losses as a function of τ and γ are investigated, as shown in Fig. 2. As to the drop port, $n_g \geq n_{awg}$ is true for all τ and γ considered, as shown in Fig. 2(a); and n_g grows as τ increases, namely light becoming “slower and slower”. However, the insertion loss acts in the same way (see Fig. 2(a)). Thus the signal will be badly distorted when the amplitude of κ is too small, although it is delayed for a relatively long time. As far as γ is concerned, a larger γ will upraise n_g and suppress loss when τ is fixed (see the solid and dashed lines in Fig. 2(a)). Fig. 2(b) shows the properties of n_g and insertion loss of the through port, and it is found that $n_g \leq n_{awg}$ for all τ and γ.