FSR decrement by proper design of micro-ring resonators for soliton-based communication systems

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Abstract— Effects of different structural parameters on free spectral range (FSR) of multi-stage micro-ring resonators (MRRs) have been investigated, while a soliton pulse is propagated. It has been shown that in the structure consisted of multi-stage MRRs, increasing MRR radius and width would decrease FSR. The main purpose of this research is to improve the functionality of multi-stage MRRs by decreasing FSR for soliton-based communication systems.

Keywords: Free spectral range; Micro-ring resonator; Soliton

I. INTRODUCTION

Micro-ring resonators (MRRs) are important components in integrated circuits. They have attracted attentions in recent years due to their compactness, high quality factor and simplicity of fabrication. Integrated MRRs do not require facets or gratings for optical feedback. MRRs have remarkable applications in optical networks, sensors, biosensors and tunable wavelength filters. Different optical pulses can be propagated in MRRs, such as Gaussian, square, soliton and so on. Soliton is the most appropriate pulse for communication applications. Solitons are especially known for their two interesting properties including localization and non-dispersive behaviors. In operation, the large bandwidth signals can be generated within MRR devices by using a soliton pulse input into nonlinear MRRs. Linear and nonlinear effects which are known respectively as group velocity dispersion (GVD) and self phase modulation (SPM) have been considered in soliton propagation in the system of MRRs. In effect, there should be a balance between the nonlinear and dispersion lengths [1]. Free spectral range (FSR), the distance between two resonance peaks, is an important parameter on soliton propagating within MRRs. The amount of FSR in soliton-based communication devices is proportional to the number of channels [2]. Propagation of soliton pulses in MRRs is widely investigated in recent years especially in long-haul communication. Generation and filtering of soliton pulses by MRRs for DWDM-based communication have been reported by Yupapin et al. [3]. In another research lower FSR has been achieved by generating a Gaussian soliton using a 1.3 μm optical pulse in MRRs [4]. Some optical characteristics can be adjusted by structural parameters, such as the research reported by Wang et al. [5]. Also in recent researches, new nonlinear micro-ring resonator double add-drop multiplexer system for generating optical communication using 1300nm Gaussian pulse [6] and new photonic biosensors with double slot (based on MRR) achieving 33nm of FSR and 580nm of quality factor are reported [7].

In this paper, effects of structural parameters on FSR of multi-stage MRRs have been studied. The structural parameters are ring radius and the width of waveguide and MRRs. By changing the structural parameters of the MRRs, systems with higher channel capacities can be achieved, which are suitable for communication applications.

II. THEORY AND STRUCTURE

MRR acts as a wavelength selecting filter. Propagating specific wavelength is the operating principle of an MRR. Wavelengths satisfying the following equation can propagate in an MRR [2]:

\[ nL = m\lambda \]  

where \( m \) is an integer, \( L = 2\pi R \) is the circumference of the MRR, \( R \) is the ring radius, \( \lambda \) is the resonance wavelength of the MRR and \( n \) is the refractive index of the MRR.

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The soliton pulse with the optical field given by the following equation is launched to the multi-stage MRRs of Fig. 1:

$$E_{in} = A \sec h \left[ \frac{T}{T_0} \right] \exp \left[ \frac{-z}{2L_D} \right]$$

(2)

where \(A\) and \(z\) are the optical field amplitude and propagation distance, respectively. \(T\) is a soliton pulse propagation time, \(T_0\) is the soliton pulse width and \(L_D\) is a dispersion length of the soliton pulse.

![Figure 1. Schematic view of two micro-ring resonators and an add/drop filter [3].](image)

It is known that, nonlinear \((L_{NL})\) and dispersion \((L_D)\) lengths are the length scales over which nonlinear or dispersion effects make the pulse become wider or narrower. Obviously, there should be a balance between the nonlinear \((L_{NL})\) and dispersion \((L_D)\) lengths for a soliton pulse to propagate in the MRR device [1].

$$L_D = T_0^2 \sqrt{\beta_2} = L_{NL} = 1/\gamma \phi_{NL}$$

(3)

where \(\gamma\), \(\phi_{NL}\) and \(\beta_2\) are the coupling loss of the field amplitude, the nonlinear phase shift and the propagation constant, respectively.

In this case, the nonlinearity of the medium is assumed to be of the Kerr-type, so the refractive index is given by [1]:

$$n = n_0 + n_2 I = n_0 + \left( n_2 A_{eff} \right) P$$

(4)

where \(n_0\) and \(n_2\) are the linear and nonlinear refractive indices, \(I\), \(P\) and \(A_{eff}\) indicate the optical intensity, optical power and effective mode core area respectively; for an MRR, \(A_{eff}\) changes in the range of 0.5 to 0.1 \(\mu m^2\) [1, 7].

Output fields are obtained from drop and throughput ports, that are given vs. input field by (5) and (6):

$$\frac{E_{out}}{E_{in}} = \frac{(1 - \kappa_1)(1 - \kappa_2) e^{-\alpha z} cos(k_2 L) + (1 - \kappa_3) e^{-\alpha z}}{1 + (1 - \kappa_1)(1 - \kappa_2) e^{-\alpha z} - 2\sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{-\alpha z} cos(k_2 L)}$$

(5)

$$\frac{E_{drop}}{E_{in}} = \frac{\kappa_2 e^{-\alpha z} cos(k_2 L)}{1 + (1 - \kappa_1)(1 - \kappa_2) e^{-\alpha z} - 2\sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{-\alpha z} cos(k_2 L)}$$

(6)

where \(E_{out}, E_{in}, E_{drop}\) are the throughput, drop and input fields respectively. \(\beta = \kappa_2 A_{eff}\) is the propagation constant, \(k_2\) is the wave number and \(n_{eff}\) is the effective refractive index of the waveguide.

We obviously know that, for propagating a soliton pulse in MRRs, there is a mathematical description, which is obtained from Maxwell’s equations. After considering some approximations in Maxwell’s equations, an equation known as the Nonlinear Schrodinger equation (NLS) would be achieved. The responses of the NLS equation are the optical solitons.

The equation can be written as follows:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\beta_2}{6} \frac{\partial^3 A}{\partial t^3} = i\gamma |A|^2 A - \frac{\alpha}{2} A$$

(7)

where \(A(z,t)\) is the pulse envelope in the presence of nonlinear and dispersion effects. \(\alpha\), \(\beta_2\) and \(\beta_3\) account for fiber losses, second-order and third-order dispersion effects. The nonlinear parameter \(\gamma = 2\alpha m_2 / (\lambda A_{eff})\) is written in terms of the nonlinear-index coefficient \(n_2\), the optical wavelength \(\lambda\) and the effective mode core area \(A_{eff}\) [1]. The above equation is a partial differential equation in which \(\beta_3\) is set to zero.

III. SIMULATION AND NUMERICAL RESULTS

The NLS equation is a nonlinear partial differential equation that does not generally lend itself to any analytic solutions. Therefore, a numerical approach is often necessary for solving the NLS. The Finite-Difference Time-Domain (FDTD) numerical method is used for the analysis of the proposed structure. In Fig. 1, the selected ring parameters are, \(R_1 = 10 \mu m, R_2 = 5 \mu m, R_3 = 20 \mu m, \kappa_2 = 0.7, \kappa_3 = 0.5\) and \(\kappa_1 = \kappa_4 = 0.1\).

System parameters are \(\lambda_0 = 1.55 \mu m, n_0 = 3.34 \ (InGaAsP/InP), A_{eff} = 0.25 \mu m^2, m_2 = 2.2 \times 10^{-17} m^2/W, \alpha = 0.5 dB/mm\) and \(\gamma = 0.1\). A soliton pulse with 40ns pulse width and 1W peak power is launched into the system.

The effects of variation of the structural parameters on the FSR are studied.

a. Effects of MRR radius on FSR

In this part, the effect of MRR radius on FSR is investigated. Obtained results are demonstrated in the following figures. FSR is theoretically obtained according to (8) by variation of the ring radius [5, 8]:

$$FSR = \Delta f \frac{\pi (\alpha A \sqrt{1 - \kappa})}{1 - \alpha A \sqrt{1 - \kappa}}$$

(8)

where \(\Delta f, A, \alpha, A = e^{-\alpha t}\) and \(\kappa\) are respectively full-width at
half maximum (FWHM), transmission loss, amplitude loss in one turn, ring radius and coupling coefficient. From (8) it can be concluded that by increasing the ring radius, the denominator would be increased more, which would lead to a decrease in FSR. FSR vs. $R_d$ radius variation for different ring resonators are depicted in Figs. 2, 3 and 4. For soliton-based communication systems in all three tables, A is the best case for its lowest FSR.

i. In the first step, $R_1$ and $R_2$ are constants but $R_d$ is variable.

![Figure 2. FSR vs. $R_d$ radius variation.](image)

ii. In the second step, $R_1$ is variable but $R_2$ and $R_d$ are constants.

![Figure 3. FSR vs. $R_1$ radius variation.](image)

iii. In the last part, $R_1$ and $R_d$ are constants but $R_2$ is variable.

![Figure 4. FSR vs. $R_2$ radius variation.](image)

In the above figures, by increasing the ring radius, FSR would be diminished, as suggested by (8).

By comparing all three above figures with (8), we find out that the experimental results are completely consistent with the calculation. So increasing the ring radius would decrease FSR.

b. Effects of the width of MRR and waveguide on FSR

Effects of the width of MRR and waveguide on FSR are being considered in this section. FSR relation can be theoretically written as follows by changing the MRR width (for rings having the same perimeter L) [8-10].

$$FSR = \frac{C}{n_r L}$$

$$n_r = n_{eff} + f_0 \left( \frac{dn_{eff}}{df} \right)$$

where $n_{eff}$, $n_{eff}$, $C$ and $f_0$ are the group index of the waveguides, the effective index of the waveguides, speed of the light and the resonant frequency, respectively.

As the width increases, attenuation coefficient of the waveguide becomes smaller; this is due to the fact that larger width provides a stronger optical confinement of the signal. So, the amount of FSR decreases by increasing the width. From (9), (10), decreasing the ring width (ring perimeter) would decrease the effective index, which would lead to a decrease in the group index $n_r$, and an increase in FSR accordingly.

Figs. 5, 6 and 7 demonstrate FSR vs. width variation for the ring resonators with different parameters.

![Figure 5. FSR vs. width variation for $R_1=10\mu m$, $R_2=5\mu m$, $R_3= (a) 20\mu m$, (b) 16$\mu m$, (c) 15$\mu m$, (d)10$\mu m$.](image)
By comparing three above figures with (10), it's understood that the simulated results are completely consistent with the calculation, that is increasing the MRR width would decrease FSR. As it is shown, the MRR width has less significant effect on FSR than MRR radius.

IV. CONCLUSION

In this paper, effects of the structural parameters such as ring radius and width on FSR have been investigated. It has been shown that increasing the ring radius would decrease FSR which is more affected by $R_1$ and $R_2$ than $R_0$. It is also indicated that FSR would be decreased by increasing the width. Changing the gap has negligible effect on FSR. Generally, it is concluded that, FSR of MRRs can be changed and adjusted for soliton-based communication systems by changing the structural parameters such as the ring radius and the width.

V. REFERENCES


