Manipulating of nanometer spacing dual-wavelength by controlling the apodized grating depth in microring resonators

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A B S T R A C T

We propose a passive photonic design for an optically pumped laser system and tunable dual-wavelength generation application by employing optical nonlinear mode coupling of two coupled III–V semiconductor microring resonators, which is connected to a pump and drop waveguide buses. One of the two rings contains a grating, whereas the other has a planar surface. The mechanism underlying the dual-wavelength generation can be explained via the resonance detuning of the spectra that results in nonlinear mode mixing. The tunability of the wavelengths can be achieved by altering the grating depth of the microring resonator and the power coupling coefficients. In the grating design of the microring resonators, we have selected a trapezoidal-profiled apodized grating to obtain low reflectivity at the sidelobes. A time-domain traveling wave (TDTW) analysis yields an InGaAsP core refractive index of 3.3. This core is surrounded by a grating InP cladding with a refractive index of 3.2. We further confirm that the propagation of a Gaussian pulse input with a power of 10 mW and a bandwidth of 0.76 ps is well confined within the system mode propagation. The results show a 2:1 fan-out of two spectrally separate signals, which can be employed for compact and high functional sources on chips.

Introduction

Fiber Bragg Grating operating as multichannel filters have been investigated in optical communication applications such as wavelength division multiplexing (DWDM) systems, where these systems offer the high capacity channel numbers for the wavelength filtering with high spectral performances. Recently, the passive and active semiconductor waveguides have been attracted as wavelength multiplexing devices due to capabilities of generating high-performance multi-wavelengths and dual-wavelength [1–3]. These devices have many applications in optical sensors as well as the THz signal generation [4]. In a research work pursued by Zhou et al, a system of stable dual-wavelength laser which is consisting of cascaded FBGs was built up in such a way, the laser wavelengths with a fixed spacing at the FBG pair’s center wavelength was performed [5]. The more recent research work was proposed by Liu et al, in which a tunable dual-wavelength configuration was demonstrated to manipulate the polarization state of each generated wavelength, where the birefringence FBG was used to stabilize the dual-wavelength laser setup [6]. Another option to generate multi-wavelength is to use photonic crystal fibers, where these materials have distinct properties such as wide range single-mode operation, large mode areas, and dispersion flexibilities which can be utilized for a wide range of applications such as wavelength-selective filters, multiplexing-demultiplexing signals, and wavelength dependent filters [7]. The recent advancement photonics devices such as microring resonators which operate in both optical-based mirrors and band-limited reflectors have been known as the most efficient devices which have many practical advantages such as owning advanced fabrication technologies and compact integrated device [8–10].

The fabrications of these devices use the planner waveguides which are suitable for synthesizing complex devices such as optical filters, wherein these owning high-contrast spectral sensitivity especially if the losses are included in the waveguide configurations. A good quality index, small and compact waveguide size and the very low loss optical channel filters can be achieved by considering both design configuration and fabrication process, in addition, to perform the system characterization and optimizations [11,12]. Among many existing optical sensors in chemical and biological applications, the sensors fabricated based on optical waveguides and integrated photonics devices such as planar optical-waveguide, directional coupler, grating-coupled waveguide, microresonator, and Mach–Zehnder interferometers demonstrate very high flexibilities and performances [13–16]. The high-quality

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factor index of the resonators and low noise detection are the requirements to obtain the smallest detectable wavelength shifts. The narrow spectral peaks with high performances can be obtained using the high-quality index resonators.

A small band radius of the resonators is necessary to perform the single mode propagation and establish the total internal reflection (TIR) law within the resonator’s structure [17,18]. In this research, we propose a coupled microring resonators comprising two microring resonators made of an InGaAsP/InP semiconductor. For the input wavelength of 1.55 µm, the nonlinear refractive index of the InGaAsP core waveguide is 2.2 × 10⁻¹⁷ m²/W [19]. The drop bus waveguide has a grating in the core area, whereas the input microring resonator does not (Fig. 1). To analyze this system, we use the time-domain traveling wave (TDTW) method, which has previously been deployed to model and simulate both passive and active microring resonators [20]. The TDTW is based on solving advection equations and is given in more detail in the study conducted by Carroll et al. [21,22]. This method can be used to characterize the spectral responses of optoelectronics devices similar to the one presented herein. The solver used in this study is PICWave from Photon Design. We studied asymmetric microring resonators to demonstrate the functionality of generating two spectrally different (dual) wavelengths. Moreover, we discuss the underlying physical principle and the performance sensitivity of the system. We designed a coupled microring resonators for the first time, capable of generating tunable dual-wavelength in the gigahertz frequency domain by altering the grating depth of the microring resonator and the power coupling coefficients using the TDTW simulation method.

Proposed coupled microring resonators

The optical signal containing both the TE and TM polarization modes enters the waveguide via a monomodal channel. The input signal exclusively contains, at least essentially, one of the said polarization modes. The propagating signal inside the microring resonators enters the grating section, thus helping to simulate the reflected spectra. As the wave confinement within the microring resonators is good, a very low bending loss can be expected. The device comprises two coupled microring resonators with different group velocities and effective indices. In other words, the microring resonator near the input is a regular photonic waveguide-based ring, whereas the microring resonator near the drop output is augmented with a polarization sensitive grating. To generate not only a frequency comb but also two specific and selective (on-demand) spectral output wavelengths, we selected two coupled resonators and detuned one from the other by augmenting it with the grating (Fig. 1). Each ring generates a frequency comb based on its free-spectral range (FSR), wherein the visibility of the fringes depends on the quality (Q) factor of the rings. The grating detunes the respective resonance peaks from the two microring resonators such that they interfere. Upon constructive interference, the signal-mixed output is generated, while the deconstructive interference reflects the signal at κ₂, thus effectively reflecting the signal. Therefore, a periodic resonance can be generated for each reflection spectrum. The grating section helps to suppress the repetition of the reflection spectrum and will allow oscillations at specific frequencies only [23]. Therefore, a comb of resonances can be generated from the Fourier transform of the created periodic grating in the microring resonator structure. As the optical mode overlaps with the grating, the modal interference is design-tunable; for instance, different resonance spacing can be generated by selecting a different medium as the top cladding or by altering the grating periods. Such a tunability is interesting for laser sources and other spectral sensitive applications, as discussed in the conclusion section [24].

The microring resonators are simulated using the InGaAsP/InP semiconductor material. In III–V semiconductors with a wide band gap material, the hetero-structure materials are more compatible, and lattice-matched compared to I–V semiconductor materials. This advantage allows performing a better mode confinement within the structures.

Recently AlGaAs/GaAs and InGaAsP/InP as III–V semiconductor materials are widely employed for integrated optoelectronic circuits. This is due to the fact that the silicon material owns an indirect bandgap and low carrier mobility which is a serious obstacle that causes decreasing its performance in many optoelectronic applications [27].

The InGaAsP core, which has a refractive index of 3.31, is surrounded by InP (n = 3.18). Table 1 lists the sequence (from top to bottom) of the semiconductor layers used in this study.

The input optical field (E₀) of the Gaussian pulse is given by the following equation [28]:

\[ E₀(z = 0, t) = T₀ \exp \left( -\frac{t^2}{2T₀^2} \right) \]

(1)

where the pulse width T₀ (related to the full width of the pulse at half maximum (FWHM), i.e., T_{FWHM} ≈ 1.665 T₀) increases with z (the pulse increases) according to the following equation.

\[ T(z) = \left[ 1 + \left( \frac{z}{L₀} \right)^{1/2} \right] T₀ \]

(2)

The variation in the peak power changes due to the group velocity dispersion (GVD) is given by the following equation.

\[ P(z) = P₀ \left[ 1 + \left( \frac{z}{L₀} \right) \right]^{2/2} \]

(3)

The dispersion length as \( L₀ = T₀^2/|\beta₂| \) and the \( \beta₂ \) as the second order coefficient of the propagation constant are the parameters indicated in Eqs. (2) and (3) [29,30]. In Eqs. (2) and (3), the term is the dispersion length of the Gaussian pulse and is the second-order coefficient term of the Taylor expansion of the propagation constant [31,32]. When the Gaussian pulse propagates within the coupled microring resonators, a resonant output is generated for each round-trip. Both the microring resonators have the same radius of 8 µm, and the power coupling coefficients are κ₁ = κ₂ = κ₃ = 0.1. The effective area is 3.03 µm², and the waveguide loss is α = 0.5 dB/mm [33]. Due to a very small radius

| Table 1 |
| Sequence of microring resonator semiconductor layers (bottom to top). |
| InP substrate (0.4 µm) (Refractive index = 3.18) |
| InGaAsP (0.38 µm) (Refractive index = 3.31) |
| InP (etch stop layer) (0.05 µm) (Refractive index = 3.39) |
| InGaAsP (0.84 µm) (Refractive index = 3.31) |
| InP (cap cladding) (0.2 µm) (Refractive index = 3.18) |

Fig. 1. Schematic of the InGaAsP/InP microring resonator semiconductor structure. Each microring resonator has a circumference of 50 µm (radius of 8 µm), and the microring resonator coupled to the drop bus waveguide has a grating in the core area.
of the microring resonator which is about 8 µm, the waveguide loss will be then \( \alpha = 0.5 \text{ dB} \times 10^{-3}/\mu\text{m} \) which shows a negligible value. Moreover, applying the grating on the microring resonator structure decrease the waveguide loss further. The decrease in the total loss for the Bragg wavelength occurred due to both reductions of the out-of-plane scattering and the absorption in waveguide [34]. Mathematically, the grating period can be calculated using Eq. (4) [35].

\[
\frac{\lambda}{n_{\text{eff}}} = 2\Lambda
\]

where \( n_{\text{eff}} \) is the mode effective index, \( \lambda \) is the Bragg wavelength, and \( \Lambda \) is the grating period. In this research, \( n_{\text{eff}} = 3.28 \) and \( \lambda = 1.55 \mu\text{m} \). Accordingly, the grating period is \( \Lambda = 0.236 \mu\text{m} \). Fig. 2 shows the cross-section of the microring resonator without and with the grating.

The apodized Bragg grating fabrication method has the advantage of owning much lower reflectivity at the sidelobes. This advantage can enhance the quality of the optical filters, where reducing the group delay tipples simultaneously causes an improvement of the dispersion compensation effects present in the grating structure. In many applications, the generated side-band can cause a crosstalk error in the WDM systems and it may have many other drawbacks such as linewidth broadening effects in high power lasers and signal instabilities in fiber lasers systems especially Q-switch fiber lasers. In order to eliminate these drawbacks, an apodized grating fabrication is recommended, in which the grating strength is lower at both ends, and it varies with respect to the grating length. Therefore, the fabrication technology of the apodized grating owns significant improvements such as suppression of the sidelobe, where the narrow bandwidth and good reflectivity are granted. By gradually varying (increasing and decreasing) the grating length along the waveguide, the reflection spectrum in an apodized form can be obtained. In many applications such as non-photosensitive materials varying the dimension of the waveguide causes forming the grating, where the grating strength can be determined by the grating depth and the duty cycle. The fabrication process of the apodized grating allows varying the parameters such as the waveguide dimensions [36].

The introduced model helps in apodizing the gratings and introducing phase shifts between the gratings in adjacent sections. In this research, a dual-wavelength can be generated with different fractions of MinHeight (grating depth). Therefore, different grating depths can be applied to the coupled microring resonator system. As the grating depths are different, the dual-wavelength generated at the throughput applications. We have applied an apodized grating on the microring resonator with a total circumference of 50 µm.
Fig. 4. Throughput outputs, (a) MinHeight = 0, (b) MinHeight = 0.1, (c) MinHeight = 0.2, (d) MinHeight = 0.3, (e) MinHeight = 0.4, (f) MinHeight = 0.5, (g) MinHeight = 0.6, (h) MinHeight = 0.7, (i) MinHeight = 0.8, (j) MinHeight = 0.9, and (k) MinHeight = 1 (no grating applied).
and drop ports have different spacing ranges, i.e., from 0.2 to 1.43 nm. The changes in the dual-wavelength spacing cause the system to behave as a sensor device with the sensitivity depending on the refractive index of the top cover cladding. The microring resonators with a grating section are used to generate comparative outputs using a very compact system and has the ability to develop the proposed system in a chip.

**Result and discussion**

Fig. 3 shows the propagation of the input pulse (with 10 mW power, FWHM of 0.76 ps, and the center wavelength of 1.55 µm) within the microring resonator semiconductor. As shown in Fig. 3, the confinement of the input light inside the microring resonator waveguide is excellent. Fig. 4 shows the throughput outputs of the microring resonator. The dual-wavelength with a tunable spacing ranging from 0.2 nm (26 GHz) to 1.43 nm (178 GHz) could be generated by varying the MinHeight fraction or the grating depth of the microring resonator coupled to the drop bus waveguide.

The fraction varies between 0 and 1. If it is “1,” no grating is applied to the microring resonator. Fig. 5 shows the dual-wavelength spacing with respect to the MinHeight fraction (grating depth) for the throughput outputs. When no grating is applied to the microring resonator, the spacing is maximum and it decreases when the grating is applied i.e., with the decrease in the MinHeight fraction. Fig. 6 shows the dual-wavelength spacing with respect to the power coupling coefficient \(\kappa\) of the microring resonators (throughput outputs).

Fig. 7. Drop port outputs, (a) MinHeight = 0.4, (b) MinHeight = 0.6, (c) MinHeight = 0.8, and (d) MinHeight = 1.

Fig. 8. Dual-wavelength spacing with respect to the MinHeight fraction for the drop port outputs.
the microring resonators, which varies between 0.1 and 0.9, for the throughput outputs. In this case, the MinHeight fraction is selected as 0.3.

Fig. 7 shows the drop port outputs. The multi-wavelength could be generated. The pulse centered at 1549 nm exhibits a dual-wavelength, because of the different dual spacing values and different MinHeight fractions such as 0.4, 0.6, 0.8, and 1. Therefore, the spacing of the dual-wavelength varies between 0.46 and 1.43 nm. The dual-wavelength side-band peaks are due to the grating section, as the presence of a wavelength varies between 0.46 and 1.43 nm. The dual-wavelength fractions such as 0.4, 0.6, 0.8, and 1. Therefore, the spacing of the dual-wavelength side-band peaks at the drop port are comparable to the throughput.

The drop-port output signals exhibit dual-wavelength behavior. When the intensity difference between the two “wavelengths” in each dual-wavelength is insignificant (lower than 1 dB), it is considered as a single passband of the filter. Therefore, the MinHeight fraction was selected between 0.4 and 1. Fig. 8 shows the dual-wavelength spacing with respect to the MinHeight fraction for the drop port outputs.

Conclusion

We have proposed a system of coupled microring resonators which is utilized to generate tunable dual-wavelength, where the nanometer spacing of the dual-wavelength is obtained. One of the recent application of the presented configuration can be a generation of millimeter waves which can be utilized to generate GHz center frequencies by beating the two closely center wavelengths of the dual-wavelength using optical photodetectors. The generated GHz center frequencies are corresponding to the spacing length between the two wavelengths. The InGaAsP/InP-coupled microring resonator, developed with apodized grating sections, was used to generate a dual-wavelength with tunable spacing ranging from 0.2 nm (corresponding to 26 GHz) to 1.43 nm (corresponding to 178 GHz). The InGaAsP/InP-coupled microring resonators comprise two microring resonators, wherein the microring resonator coupled to the drop bus waveguide has grating in the core area. The total circumference of each microring resonator is 50 μm. The simulated results are based on the TDTW method. We investigated the propagation of an input Gaussian pulse with a 10 mW power and a bandwidth of 0.76 ps within the proposed coupled microring resonators. Stable, single-mode, dual-wavelength lasers have important applications in fiber sensors. The beat between the two laser wavelengths will generate a millimeter-range wave, which can be used in optical communications. In this research, the spacing between the generated dual-wavelength varies with respect to the grating depth, which is represented using the MinHeight fraction. The different grating profiles would affect the outputs of the coupled microring resonators, and consequently, would vary the spacing between the two center wavelengths in the dual-wavelength. The spectral tunability of cavities can help make next-generation integrated nanophotonic devices and circuits to include light sources and emitters, reconfigurable switches and modulators, surface-sensitive devices, and application in on-chip data communication ideally with the nanoscale footprint for high electro-optic device efficiencies. For instance, the microring resonators, therefore, can be used as sensor devices based on an evanescent wave interacting with the surrounding cladding of the system made of semiconductors or used for millimeter wave generation in optical communications.

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References