Accepted Manuscript

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PII: S2211-3797(18)31737-6
DOI: https://doi.org/10.1016/j.rinp.2018.08.006
Reference: RINP 1596

To appear in: Results in Physics

Received Date: 23 July 2018
Revised Date: 1 August 2018
Accepted Date: 5 August 2018

Please cite this article as: Amiri, I.S., Anwar, T., Zakaria, R., Yupapin, P., TE-like mode analysis of microsystem InGaAsP/InP semiconductor resonator generating 20 GHz repetition rate pulse trains, Results in Physics (2018), doi: https://doi.org/10.1016/j.rinp.2018.08.006

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TE-like mode analysis of microsystem InGaAsP/InP semiconductor resonator generating 20 GHz repetition rate pulse trains

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ABSTRACT:

In microsystem technologies, the microring resonators (MRRs) can be used as a filter device. A wavelength-selective modified add-drop MRR filter is used for adding and dropping a particular wavelength in order to control the light propagation within the system. The spectrum of the mode-locked laser could be generated using a fiber laser loop consisting of active gain medium, EDF, Lumies 980 nm laser diode (LD), wavelength division multiplexer (WDM), isolator, a polarization controller (PC) and carbon nanotube (CNT). The multi-mode-locked laser could be generated at the through and drop port of the system after the mode-locked pulse from the fiber laser circulate within the MRR filter. Here, the mode-locking relies on a fiber laser setup, where the MRR filter has been modeled using the Fimmwave and PICWave softwares. We present this photonic circuits simulator based on the time-domain traveling wave (TDTW) method, provides modeling both active and passive photonic circuits. The pulse bandwidth and repetition of the train mode-locked pulses generated by the fiber laser setup are 0.65 ps and 30 MHz respectively. Using the MRR filter, the drop port output pulses show the FSR and FWHM of 172 pm (20 GHz) and 8.3 pm respectively. The finesse and the Q-factor are approximately 20.72 and 1.9×10^5 respectively.

Keywords: Microring resonator (MRR); TE-like Mode, InGaAsP/InP semiconductor, TDTW

1. INTRODUCTION

In order to transmission of communication signals, soliton-based optical communication systems can be a good choice [1]. Dispersion and nonlinearity can interact to produce permanent and localized waveforms [2]. For optical communication, channels are needed, where the fiber can be considered as the channel between other types of channels required for optical telecommunication and communication applications. If the high bit rate communications are required for the long-distance communications, the phenomenon as dispersion can be a major issue. Therefore, solitons will be an effective tool to solve this problem. As a filter device, the microring resonators (MRRs) can be utilized in which by using the suitable parameters of the device and controlling the output signals we can generate signals
in the form of soliton [3]. Optical soliton communication requires generating of high repetition rate chirp-free pico-second pulses, which have the shape of “sech” [4, 5]. The applicable wavelength region for the source to operate is near 1.55 µm [6]. The mode-locked semiconductor lasers can also be utilized for optical soliton communication and are frequently selected due to the generation of a pulse train which are chirp-free [7]. In the case of long-distance optical fiber communication systems utilizing soliton pulses, these systems are competing with current transmission schemes such as the wavelength division multiplexing (WDM) [8]. Solitons are going to persist if they offer higher bit rates without an increase of the cost per bit. In telecommunication systems, multi-gigahertz pulse trains are required [9]. One wave to increase the repetition rate of communication pulses is to use MRR filters. MRR-based photonic systems can also be used for the purpose of photonic compressive sensing (CS), resulting to transmit and receive very high frequency signals in the communication systems. Compressed sensing technique can reduce the amount of collection data significantly via very few sampled data. Some efficient CS algorithms can be found in [10-12].

The filtering function of certain wavelengths in the MRR can be utilized to design new filter devices which are made of several coupling optical MRRs [13]. Various types of MRRs have been fabricated such as the MRRs owning only a single bus waveguide, owing to double bus waveguides, multiple and racetrack MRRs [14]. The resonance wavelength of the transmitted light of the MRRs can be changed to other wavelengths and bands by changing the dimensions of the device [15]. This capability can be used to control the waveguide outputs for different wavelength band and many applications accordingly. The repetition rate of pulses in a fiber laser setup which is generating mode-locked lasers is proportional to the cavity length [16]. In passive photonics devices, the resonance frequency depends on the phase-matching of the cavity modes [17]. Waveguides which are used to generate TE modes are preferred to integrate with edge-emitting semiconductor lasers which operate in the TE modes [18]. The structure design of the MRR is presented and the mode propagation within the waveguide is analyzed. A high repetition rate pulse train can be generated using a technique which can result in generating of high-speed communication signals, and millimeter/micrometer waves for photonics applications [19]. In this study, the MRR filter is connected to the fiber laser setup to generate the multi-wavelength at the through and drop port of the system. The free spectral range of the generated signals is 20 GHz confirming the pulse repetition rate of 20 GHz [19].

2. SIMULATION OF THE MRR

The system of MRR filter and its structure is shown in Figure 1. The spectrum of the mode-locked laser generated by a fiber laser loop setup is introduced into the input port of the MRR.
Here, the InGaAsP/InP material is used to simulate the MRR. The method as time-domain traveling wave (TDTW) is used to calculate the transfer function of the microsystem. For the operating wavelength of 1.55 μm, the nonlinear refractive index is considered as 2.2×10^{−17} m^2/W. The etch stop layer has been included in the structure in order to perform a precise control on the propagating fundamental modes. Table 1 shows the waveguide parameters.

Table 1: MRR waveguide parameters

| Material                | Thickness | Refractive index |
|-------------------------|-----------|------------------|
| InP (cap cladding)      | 0.2 μm    | 3.18             |
| InGaAsP                 | 0.84 μm   | 3.31             |
| InP (etch stop layer)   | 0.02 μm   | 3.39             |
| InGaAsP                 | 0.38 μm   | 3.31             |
| InP (substrate)         | 0.4 μm    | 3.18             |

3. RESULTS AND DISCUSSION

In this device, mode-locking relies on a fiber laser setup, where the MRR filter has been modeled using the PICWave software. The experiment setup of the fiber laser is illustrated in Figure 2. The Leikki Er80-8/125 EDF which is highly doped, and it has a length of 0.9 m is utilized as an active gain medium. The NA which is representing the numerical aperture is 0.21 to 0.24. Here a Lumics 980 nm laser diode (LD) is used connecting to the wavelength division multiplexer (WDM).

Fig. 2. Fiber laser setup, LD: laser diode, CNT: carbon nanotube, TBPF: tunable bandpass filter, OSA: optical spectrum analyzer, SA: Radio frequency (RF) spectrum analyzer, PD: photodetector

The lunch pump power has been selected to 50 mW (17 dBm). The autocorrelation trace shows the sech^2 pulse profile, which results in the soliton generation. The pulse has
a bandwidth of 0.65 ps. Figure 3 shows the generated mode-locked spectrum laser, the time-domain profile of the pulse and RF signals.

![Figure 3](image)

**Fig. 3.** (a): Spectrum of the mode-locked laser pulse, (b): Time-domain profile of (a), (c): Radio frequency (RF) signals with 30 MHz of FSR

The parameters of the simulated MRR filter are listed in Table 1.

**Table 1.** Parameters of the MRR system

| Parameter | Value |
|-----------|-------|
| $R_{ad}$  | 1.3 mm |
| $R_{ring}$ | 128 µm |
| $\kappa$ | 0.5 |
| $\kappa_1$ | 0.02 |
| $\kappa_2$ | 0.02 |
| $n_0$ | 3.31 |
| $n_2$ (m²/W⁻¹) | 2.2×10⁻¹³ |
| $A_{eff}$ (µm²) | 2.97 |
| $\alpha$ (dBmm⁻¹) | 0.5 |
| $\gamma$ | 0.1 |

The input pulse propagates within the MRR filter, where the Figure 4 shows the fundamental mode propagating within the waveguide. The mode propagation effective area of 2.81 µm², effective index of 3.28, group index of 3.31, and dispersion (ps/nm/km) of -51 is achieved.
Fig. 4. Fundamental mode propagation within the MRRs waveguide, (a) Propagating mode profile, (b) Cross section view, (c) 3D view, where the effective area of the mode propagation is 2.81 µm², effective index is 3.28, group index is 3.31, dispersion (ps/nm/km) is -51

The throughput and drop port output pulses are shown in Figures 5 and 6.

Fig. 5. Throughput port output signals
The drop port output pulses show the FSR and FWHM of 172 and 8.3 pm respectively. The pulse duration and repetition of the train mode-locked pulses are 3 ps and 20 GHz respectively.

The finesse of the generated pulses is 20.72, and the Q-factor is \( \sim 1.9 \times 10^5 \). Increasing the MRR’s radius causes increasing of the Q-factor of the filter which leads to a reduction of the bending loss [20]. The spectral range of wavelength resonating within the microsystem is the critical factor which can determine the quality factor and system performance [21]. The latter factor as a quality factor can be used to determine the losses of the transmitting signals as the large losses occur in low-quality factor systems [22]. The modes generated in the bent waveguides are leaky mode types, in which the bending loss increases with decreasing the MRR radius [23, 24]. The TE-like modes are presented and shown in Figure 8.
Mode 1: (Left) the mode propagation profile (Right) the cross sectional profile of the mode, effective index=3.27, group index=3.31, effective area=2.98 $\mu$m$^2$, dispersion (ps/nm/km)=-56

Mode 2: effective index=3.25, group index=3.32, effective area=3.70 $\mu$m$^2$, dispersion (ps/nm/km)=-108

Mode 3: effective index=3.23, group index=3.28, effective area=5.32 $\mu$m$^2$, dispersion (ps/nm/km)=-232

Mode 4: effective index=3.22, group index=3.27, effective area=3.34 $\mu$m$^2$, dispersion (ps/nm/km)=-76
Mode 5: effective index=3.21, group index=3.31, effective area=5 µm², dispersion (ps/nm/km)=5

Mode 6: effective index=3.20, group index=3.32, effective area=3.68 µm², dispersion (ps/nm/km)=41

**Fig. 8.** Number of TE modes propagating within the waveguide section including effective index, group index, effective area and dispersion for each mode

In the conditions when the resonances are established, the cavity modes namely Hermite–Gaussian modes can be generated in systems which have parabolic mirrors or homogeneous media [25]. The Gaussian modes can be examples of the cavity modes, where, in such modes, the Gaussian function is used to determine the field distributions in the system. The details of the cavity resonator can define and determine many factors such as the beam radius or the wavefronts curvature’s radius which are necessary to evaluate the performance of the microsystem [26]. Besides, the resonator systems can have higher-order modes which have more complicated field distributions compared to the Gaussian modes [27]. The modes propagating in the optical resonators namely resonant cavities may have different propagating constant or transverse intensity profile. These types of modes are emphasized by the term “transverse modes” or “lateral modes” in optical cavity systems [28]. The fundamental modes have more simple intensity profiles compared to the higher-order transverse modes [29]. We have calculated the orthogonality of the modes, which is a very good test of the accuracy of our calculation. The overlapping of the mode number 1 with the other modes is presented in the following table.

| mode’s number | Overlap          |
|---------------|------------------|
| 2             | 1.7×10⁻⁷         |
| 3             | 3.16×10⁻⁴        |
| 4             | 9.34×10⁻¹⁰       |
| 5             | 2.73×10⁻⁴        |
| 6             | 4.7×10⁻⁴         |
This will calculate the largest overlap between different modes. Ideally, this should be zero. This is a very acceptable value as we should be typically aiming at values below $10^{-3}$, ideally below $10^{-4}$. The propagation constant, dispersion, group index and the effective area of the TE-like modes are presented in Figures 9-12.

Fig. 9. The propagation constant of the modes versus the wavelength (µm)

Fig. 10. Dispersion (ps/nm/km) of the modes versus the wavelength (µm)

Fig. 11. Group index of the modes versus the wavelength (µm)
The fundamental TE-mode polarization fraction is typically between 0.95 and 1 (nearly pure TE mode), whereas the other polarizations are not pure polarization. These effects can be used to design polarization converters.

4. CONCLUSION

A system capable of multiple mode-locked soliton transmissions will contain a modified MRR. Generation of the mode-locked spectrum is performed via a laser cavity. The multi-mode-locked laser is generated at the through and drop port of the MRR filter. The smaller MRR is used to filter the chaotic signals so the clear signals from the output ports can be obtained. In this device, mode-locking relies on a fiber laser setup, where the modified add-drop filter has been modeled using the Fimmwave and PICWave softwares. The mode-locked laser spectrum with a FWHM width of 0.65 psec measured by the autocorrelation trace is input into the MRR filter. The through and drop port output pulses of the MRR filter show generation of equaled spaced multi-mode-locked lasers. The finesse F is approximately 20.72, and the Q-factor, which is is ~1.9×10^5. This shows that the proposed and demonstrated system have high performance.

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| InGaAsP                        | 0.84 µm   | 3.31             |
| InP (etch stop layer)          | 0.02 µm   | 3.39             |
| InGaAsP                        | 0.38 µm   | 3.31             |
| InP (substrate)                | 0.4 µm    | 3.18             |