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HALF-PANDA RING RESONATOR USED TO GENERATE 100 MHZ REPETITION RATE FEMTOSECOND SOLITON

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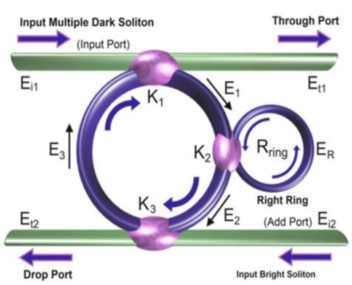
Graphical abstract



Abstract

Interferometric measurement techniques have been employed in research and industry for investigations into propagation behavior aspects of the optical solitons within semiconductor lasers. The half-PANDA ring resonator system introduced in this paper consists of an add/drop multiplex connected to a microring resonator on the right side, where the output powers can be controlled by specific parameters. The collision of dark and bright solitons occurs inside the system in which femtosecond (fs) optical solitons with 100 MHz repetition rate form the through and drop port outputs of the system. A trapping force is produced via the add port signals that constitute the input powers; thus the femtosecond optical soliton are generated and controlled within the half-PANDA ring resonator. The results of the soliton signals are obtained based on the iterative method technique in which a number of experimental and practical parameters are employed. These circumstances allow for manipulation of the trapping bandwidth by means of system parameter alterations. The input powers of the dark and bright solitons are 5.12 mW and 4 mW respectively. The full width at half maximum (FWHM) of the through and drop port output signals are 35 and 76 femtoseconds respectively correspond to 0.76 and 1.56 terahertz (THz) in frequency domain, where the repetition rate of the solitons is 100 MHz.

Keywords: Half-panda ring resonator, femtosecond soliton, repetition rate, iterative technique

Abstrak

Teknik pengukuran interferometrik telah digunakan dalam penyelidikan dan industri untuk penyelidikan dalam aspek tingkah laku perambatan soliton optik dalam semikonduktor laser. Sistem cincin separuh PANDA yang diperkenalkan pada kertas kerja ini mengandungi sebuah multipleks penambah/lepasan yang dihubungkan dengan resonator cincin mikro di sebelah kanan, di mana kuasa keluaran boleh dikawal oleh parameter tertentu. Perlanggaran soliton gelap dan terang berlaku di dalam sistem di mana femtosaat (fs) soliton optik dengan kadar pengulangan 100 MHz terbentuk melalui sistem penambah/lepasan. Satu pasukan memerangkap dihasilkan melalui isyarat pelabuhan tambah yang membentuk kuasa input. Dengan itu soliton optik femtosaat dijana dan dikawal dalam cincin setengah PANDA. Keputusan isyarat soliton diperolehi berdasarkan teknik kaedah lelaran dimana beberapa parameter eksperimen dan praktikal digunakan. Keadaan ini membolehkan manipulasi jalur lebar memerangkap dengan menggunakan apa-apa perubahan pada parameter sistem. Kuasa input daripada soliton gelap dan terang adalah masing-masing 5.12 mW dan 4 mW. Lebar penuh pada separuh maksimum (FWHM) selepas melalui pelabuhan isyarat output penambah/lepasan ialah masing-masing 35 dan 76 femtosaat, sesuai dengan 0.76 dan 1.56 Terahertz

(THz) dalam domain frekuensi, di mana kadar pengulangan daripada soliton adalah 100 MHz.

Kata kunci: cncin setengah-PANDA, soliton femtosaat, kadar pengulangan, teknik lelaran

1.0 INTRODUCTION

Optical ring waveguide resonators are useful components for wavelength filtering [1], multiplexing, switching and modulation [2]. The main performance characteristics of these resonators are the free-spectral range (FSR), the finesse (or Q-factor), the transmission at resonance, and the extinction ratio [3]. The major physical characteristics underlying these performance criteria are the size of the ring, the propagation loss, and the input and output coupling ratios (equivalent to the reflectivities of a Fabry–Perot resonator) [4]. On the other hand, strongly guiding ring waveguides with very large lateral refractive index contrast (air-semiconductor-air) can have diameters as small as 1–2 μm with negligible bending loss. Therefore, compared with the weakly guiding waveguide, the strongly guiding microcavity can be up to 1000 times smaller. Because of the small size, the propagation loss in the cavity is also negligible [5]. Consequently, both the FSR and the finesse are much larger for this resonator. Our used software accurately calculates the physical properties of guided modes in truly arbitrary waveguide geometries [6]. In an optical resonator, circulating light is confined within a small volume. When the resonant condition is met, the optical power becomes resonantly enhanced up to a factor approximating cavity finesse [7]. Such resonant enhancement, combined with a significantly increased optical path length, makes ring and racetrack resonators an ideal device platform for both fundamental investigations and practical applications based on photon-matter interactions [8, 9]. Over the last three decades, interferometric measurement methods have been applied in research and industry for investigations into transmission and receiving aspects of optical communication components [10, 11]. Ring resonators are waveguide realizations of Fabry-Perot resonators, and easily integrate in array geometries for implementation of many useful functions [12, 13]. In general, the temporal and spectral shape of a short optical soliton pulse changes during propagation in a transparent medium due to the Kerr effect and chromatic dispersion [14, 15].

Under certain circumstances, however, the effects of Kerr nonlinearity and dispersion can exactly cancel each other, apart from a constant phase delay per unit propagation distance, so that the temporal and spectral shape of the pulses is preserved even over long propagation distances [16]. In particular, the nonlinear phase response of ring resonators will produce a specific intensity output function [17]. The novel system introduced in this paper consists of a modified add/drop multiplex, where the output powers of the system can be controlled by specific parameters [18].

Controlling of dark-bright soliton propagations within this semiconductor add/drop multiplexer allows for promising applications, in which the generated intense optical field can be configured as an optical soliton [19]. The collision of dark and bright soliton pulses occurs inside the half-panda ring resonator system in which femtosecond optical soliton form the interior signals and the through and drop port outputs of the system [20].

These dark and bright soliton pulses are self-guided during propagation through the nonlinear waveguides [21]. A transceiver can be integrated and operated using a single device based on this system, and the advantages of a transmitter being fabricated on-chip or operated alternately by a single device implies associated benefits of reliability, compactness, and efficiency [22]. Exciting new technological progress, particularly in the field of tunable narrow band laser systems, optical trapping and storing and the microring resonator interferometers, provide the foundation for the development of new transmission techniques [23].

2.0 THEORY OF THE MODELED RING RESONATOR SYSTEM

Figure 1 shows the modified add/drop filter that is a prerequisite for optical femtosecond generation. The electric field E_R is the circulating field within the ring at the right side of the centered ring. Parameters of the half-panda ring resonator are of the design of the panda ring resonator structure and its application in optical trapping as reported by amiri [24]. A trapping force is produced via the add port signals that constitute the input powers; thus the optical soliton are generated and controlled within the half-panda ring resonator. The input intensity powers, particularly in the add port of the system, are the key parameters allowing significant manipulation of the optical soliton, and this control over light intensity and velocity is a highly attractive feature for medical applications [25].

The rings are modelled using the InGaAsP/InP semiconductor with InGaAsP core having refractive index of 3.31 surrounded by InP (n = 3.18). The nonlinear refractive index is 2.2×10^{-17} m^2/W for the wavelengths around 1.5 μm. InGaAsP/InP photonic semiconductors are an ideal platform for nonlinear because they exhibits some strong nonlinear effects such as Kerr nonlinearity. The used semiconductor layers sequence (from top to bottom) is shown in Table 1.

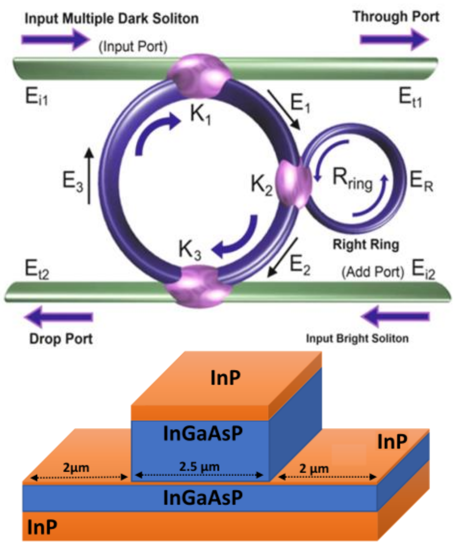


Figure 1 Top: Schematic diagram of a half-panda ring resonator, Bottom: proposed structural

Table 1 Semiconductor layers sequence (from top to bottom)

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

The ring system allows for internal propagation of an inputted laser pulse. This system contains a nonlinearity of Kerr effect type that causes the refractive index (*n*) of the medium to vary, and is described by [26]

$$n = n_0 + n_2 I = n_0 + \frac{n_2}{A_{eff}} P \tag{1}$$

with n_0 and n_2 as the linear and nonlinear refractive indexes respectively. Optical intensity is labeled as *I*, and optical power expressed as *P*. A_{eff} represents the effective mode core area. Effective mode core areas range from 1 to 5 μm^2 for a ring resonator design, and the parameters are determined by the selection of material (InGaAsP/InP) used in the ring construction [27]. The input optical fields of the dark and bright soliton pulses are given by [28]

$$E_{i1}(t) = A \tanh\left[\frac{T}{T_0}\right] \exp\left[\left(\frac{z}{2L_D}\right) - i\omega_0 t\right] \tag{2}$$

$$E_{i2}(t) = A \operatorname{sech}\left[\frac{T}{T_0}\right] \exp\left[\left(\frac{z}{2L_D}\right) - i\omega_0 t\right] \tag{3}$$

T is a soliton pulse propagation time in a frame moving at the group velocity, *A* and *z* are the optical field amplitude and propagation distance respectively. $T = t - \beta_1 \times z$, where β_1 and β_2 are the coefficients of the linear and second order terms of the Taylor expansion of the propagation constant respectively [29]. The term $L_D = T_0^2 / |\beta_2|$ represents the dispersion length of the soliton pulse, with the frequency shift of the soliton being ω_0. This solution describes a temporal soliton, which is defined as a pulse that maintains a temporal width invariance as it propagates. The calculation of soliton peak intensity $\left(\left|\beta_2 / \Gamma T_0^2\right|\right)$ allows for T_o to be known. A soliton pulse in the micro-ring resonator (MRR) device requires an equal balance achieved between the dispersion length (L_D) and the nonlinear length ($(L_{NL} = 1/\Gamma \Phi_{NL})$), with $\Gamma = n_2 \times k_0$. i.e. $L_D = L_{NL}$. These length aspects are the scale over which dispersion or nonlinear effects make the beam become wider or narrower.

A normalized resulting resonant output gives rise to represent the ratio between the output and input fields $E_{out}(t)$ and $E_{in}(t)$. An formula of the input and output signals in each round-trip of a single ring resonator is provided by [30]

$$\left|\frac{E_{out}(t)}{E_{in}(t)}\right|^2 = (1-\gamma)\left[1 - \frac{(1-(1-\gamma)x^2)\kappa}{(1 - x\sqrt{1-\gamma}\sqrt{1-\kappa})^2 + 4x\sqrt{1-\gamma}\sqrt{1-\kappa}\sin^2(\frac{\phi}{2})}\right] \tag{4}$$

Looking at the principle functions of the Fabry-Pérot cavity, from equation (4), one can perceive the same concepts for the microring resonator systems as it has an input and an output mirror with a fully reflecting mirror and field reflectivity $(1-\kappa)$. Here, κ is the coupling coefficient and $x = \exp(-\alpha L/2)$ represents a round-trip loss coefficient, $\phi_0 = kLn_0$ and $\phi_{NL} = kLn_2|E_{in}|^2$ are the linear and nonlinear phase shifts, and $k = 2\pi/\lambda$ is the wave propagation number in a vacuum [31]. L and α are waveguide length and linear absorption coefficient respectively. Solutions to equation (3) are determined by means of iterative methods in this study. Interior electric fields of the half-panda ring resonator system are given by the following equations [32]

$$E_1 = \sqrt{1-\gamma_1} \times [E_3 \times \sqrt{1-\kappa_1} + j\sqrt{\kappa_1} \times E_{i1}] \tag{5}$$

$$E_2 = E_R \times E_1 \times e^{\frac{-\alpha L}{4} - jk_n \frac{L}{2}} \tag{6}$$

$$E_3 = \sqrt{1-\gamma_3} \times [E_2 \times \sqrt{1-\kappa_3} + j\sqrt{\kappa_3} \times E_{i2}] \tag{7}$$

$$E_R = E_1 \times \left\{\frac{\sqrt{(1-\gamma_2)\times(1-\kappa_2)} - (1-\gamma_2) \times e^{\frac{-\alpha}{2}L_R - jk_n L_R}}{1 - \sqrt{(1-\gamma_2)\times(1-\kappa_2)} \times e^{\frac{-\alpha}{2}L_R - jk_n L_R}}\right\}. \tag{8}$$

κ is the coupling coefficient. The loss is presented by α and γ is the key parameter for the fractional coupler intensity loss. The circumferences of the centered and left rings are $L=2\pi R$ and $L_R=2\pi R_{ring}$ respectively, with R and R_{ring} as the radii of the rings. Two complementary optical outputs of the system, E_{t1} and E_{t2}, representing optical fields of the throughput and drop ports respectively can be introduced as

$$E_{t1} = -C_1C_2y_2\sqrt{\kappa_1}E_{i2}e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}} + \left[\frac{C_2C_3\kappa_1\sqrt{\kappa_2}E_RE_{i1}(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}})^2 + C_3C_4y_1y_2\sqrt{\kappa_1\kappa_2}E_RE_{i2}(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}})^3}{1-C_1C_2y_1y_2E_R(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}})^2}\right] \quad (9)$$

$$E_{t2} = C_2y_2E_{i2} + \left[\frac{C_1C_2\kappa_1\sqrt{\kappa_1\kappa_2}E_RE_{i1}e^{-\frac{\alpha L}{2}-jkn\frac{L}{2}} + C_1C_3y_1y_2\sqrt{\kappa_2}E_RE_{i2}(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}})^2}{1-C_1C_2y_1y_2E_R(e^{-\frac{\alpha L}{2}-jk_n\frac{L}{2}})^2}\right]. \quad (10)$$

Here, $C_1=\sqrt{1-\gamma_1}$, $C_2=\sqrt{1-\gamma_2}$, $C_3=1-\gamma_1$, $C_4=1-\gamma_2$, $y_1=\sqrt{1-\kappa_1}$,dna $y_2=\sqrt{1-\kappa_2}$.

Cancellation of chaotic noise can be achieved by appropriate manipulation of the particular parameters of the smaller microring resonator, wherein expected pulses can be recovered by the particular users.

3.0 RESULTS AND DISCUSSION

Results of the femtosecond optical soliton are generated based on the iterative method theory used for the half-panda ring resonator system, in which a number of experimental and practical parameters are employed. Multiple central wavelengths of the dark soliton pulses collide with input bright soliton pulses input at the add port of the system. These circumstances allow for manipulation of the trapping bandwidth by means of system parameter alterations. The input powers of the dark and bright soliton pulses are 5.12 mW and 4 mW respectively. Figure 2 shows these input powers across a wavelength range. The effective core areas is A_{eff}=3.03 μm^2. The waveguide and coupling losses are $\alpha = 0.5$ dBmm^{-1} and $\gamma = 0.1$ respectively. Parameters of the system that are kept static include λ_0=1.5 μm, n_0=3.31 and nonlinear refractive index n_2=2.2×10^{-17} m^2/W. The ring radii are R=15 μm and R_{ring}=5 μm and the coupling coefficients κ_1 = 0.12, κ_2 = 0.5 and κ_3 = 0.35, such that the optical soliton can be generated at different central wavelengths ranging from λ_0 = 1.4 μm to λ_0 = 1.6 shown in Figure 3.

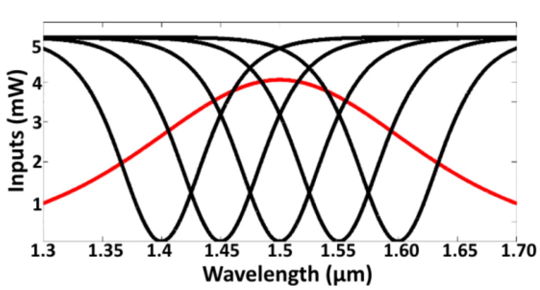


Figure 2 Input multiple dark soliton pulses and bright soliton

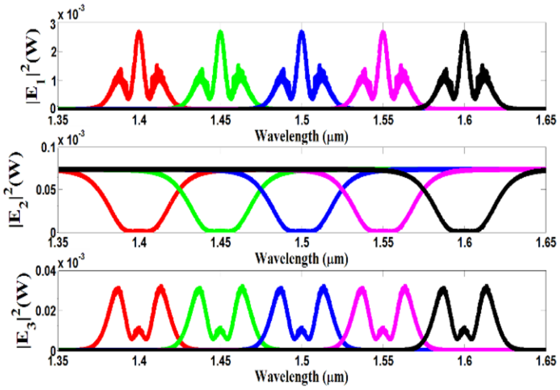


Figure 3 Results of the optical soliton generation

Figure 4 shows the through and drop port outputs of the ring system with ultra-short bandwidth in the femtosecond region that is highly appropriate for optical communication applications. The FWHM of the through and drop port output signals are 35 and 76 femtoseconds respectively.

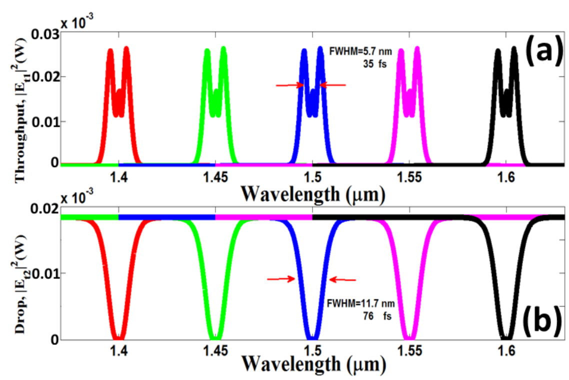


Figure 4 Pulses resulting from the optical soliton (a): Pulse optical bandwidth is 35 femtoseconds, and (b): Pulse optical bandwidth is 76 femtoseconds

The bandwidth or the FWHM in frequency domain are as 0.76 THz and 1.56 THz for the through and drop port output signals respectively. The repetition rate of the pulses are 100 MHz. Technological progress, particularly in the field of tunable narrow band laser systems, multiple transmission, and MRR systems, provides the foundation for the development of new transmission techniques, where the application of this device provides a new nano-scale interpretation of hybrid interferometer.

4.0 CONCLUSION

This paper presenting generation of dynamic soliton by using a modified add/drop multiplexer half-panda ring resonator system in order to generate femtosecond optical solitons for many applications in medical and engineering. Suitable utilization of dark-bright soliton input powers is reported, and details are provided on femtosecond bandwidth adjustments and the controllable and storage aspects of the optical solitons. A description of soliton generated with FWHM of 35 and 76 femtoseconds corresponds to 5.7 and 11.7 nanometers respectively and repetition rate of 100 MHz details successful modeling and simulation. The application of this device provides a new nano-scale interpretation of hybrid interferometer.

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