Novel tunable and storage light source generated by a soliton pulse in a micro-ring resonator system for new soliton communication bands

Jalil Ali
Khuntong Sarapat
Universiti Teknologi Malaysia
Institute of Advanced Photonics Sciences
Skudai
Johor Bahru Takzim 81310
Malaysia

Preecha P. Yupapin, MEMBER SPIE
King Mongkut's Institute of Technology Ladkrabang
Advanced Research Center for Photonics
Chalongkrung Road
Bangkok 10520
Thailand
E-mail: kypreech@kmitl.ac.th

Abstract. We propose a novel system of broadband source generation using a common soliton pulse (i.e., with center wavelength at 1.55 μm) propagating within a nonlinear micro-ring resonator system. The system consists of a micro-ring resonator system incorporating an add/drop filter, whereby the large-bandwidth signals can be generated, stored, and regenerated within the system. By using the appropriate parameters relating to the practical device such as micro-ring radii, coupling coefficients, and linear and nonlinear refractive index, we found that the obtained multisoliton pulses have shown the potential of application for dense wavelength-division multiplexing (DWDM), whereby the different center wavelengths of the soliton bands can be obtained via the add/drop filter, which can be used to increase the communication channel capacity in the communication network. The best free spectra range (FSR) and FWHM of the results obtained are 14 nm and 100 pm, respectively, which allows an increase in channel capacity of at least 10 times in only one center wavelength. [DOI: 10.1117/1.3159874]

Subject terms: soliton communication; tunable light source; storage light source; super dense wavelength division multiplexing (SDWDM).

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1 Introduction

The demand for communication channels and network capacity is increased significantly every year, and, up to now, the large user demand remains. Therefore, the search for new techniques is needed, and is focused on the increase in communication channel and network capacity. Recently, an interesting result of a technique that can be used to fulfill the large demand of channel capacity has been reported.[1] Thus report has shown that the signal bandwidth can be stretched (i.e., enlarged) and compressed by using a soliton pulse propagating within a nonlinear micro-ring system.[2–4] By using such a scheme, an increase in communication channels is plausible. Furthermore, large soliton output power is obtained, which is available for long-distance communication links. However, several problems must be resolved, for instance, the problem of soliton–soliton interaction and collision,[5] and a waveguide structure to which the broadband soliton can be confined.[6] For further reading about soliton-behaviors and applications, many of the soliton-related concepts in fiber optics are described by Agrawal.[7] In this work, we propose a novel technique that can be used to generate new soliton communication bands (wavelength bands), whereby the common soliton pulse, i.e., a soliton source at the center wavelength of 1.55 μm, is the initial input signal. After the soliton pulse is input into the system, the soliton bands at the required center wavelengths can be stored and filtered by using an add/drop filter.[8] In application, the use of super dense wavelength division multiplexing (SDWDM), with a long-distance link is available. Moreover, the concept of a personal channel and network may be plausible due to the very large available bandwidths. However, the problem of the soliton interaction and collision must be resolved, which can be avoided by the specific free spectral range (FSR) design.

2 Operating Principles

Initially, the optimum energy is coupled into the waveguide by a larger effective core area device, i.e., ring resonator, as shown in Fig. 1. Then the smaller devices are connected to form the storage unit. The ring parameters, i.e., ring radii, R_1, R_2, and R_3, are chosen relative to the practical problem, where the continuous reduction of ring radius of the ring devices is required to keep the small coupling losses due to the different core effective areas, for instance, from 15 μm to 10 μm and 5 μm. The smallest fabricated ring radius so far[9] is 4 μm. Furthermore, the coupling coefficients are also important parameters, where the required output power, free spectral range, and spectral width are the key point of the design. The technique that can be used to control and store the dominant output mode is reported in Ref. 8.The filtering characteristic of the optical signal is presented within a ring resonator and an add/drop filter, where the suitable parameters can be controlled to obtain the required output spectra. To maintain the soliton pulse propagating within the ring resonator, a suitable coupling power into the device is required, whereby the interference signal is a minor effect compared to the loss associated to the direct passing through. A soliton pulse is introduced

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into the multistage micro-ring resonators, and the input optical field (E_{in}) of the soliton input is given by.[8]

$$E_{in}(t) = A \sec h\left[\frac{T}{T_0}\right]\exp\left[\left(\frac{z}{2L_D}\right) - i\omega_0 t\right], \tag{1}$$

where A and z are the optical field amplitude and propagation distance, respectively. T is the soliton pulse propagation time in a frame moving at the group velocity, $T=t-\beta_1^* z$, where β_1 and β_2 are the coefficients of the linear and second-order terms of Taylor expansion of the propagation constant. $L_D=T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse. T_o in the equation is the soliton pulse propagation time at initial input, where t is the soliton phase shift time, and the frequency shift of the soliton is ω_0. This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a *temporal soliton*. When a soliton peak intensity ($|\beta_2/\Gamma T_0^2|$) is given, then T_o is known. For the soliton pulse in the micro-ring device, a balance should be achieved between the dispersion length (L_D) and the nonlinear length ($L_{NL}=(1/\ \Gamma\phi_{NL})$, where $\Gamma=n_2^* k_0$ is the length scale over which dispersive or nonlinear effects make the beam wider or narrower. For a soliton pulse, there is a balance between dispersion and nonlinear lengths; hence, $L_D=L_{NL}$.

When light propagates within the nonlinear material (medium), the refractive index (n) of light within the medium is given by

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}}\right)P, \tag{2}$$

where n_0 and n_2 are the linear and nonlinear refractive indexes, respectively. I and P are the optical intensity and optical power, respectively. The effective mode core area of the device is given by A_{eff}. For the micro-ring and nano-ring resonators, the effective mode core areas range from 0.50 to 0.1 μm^2 (Ref. 9), where it was found that a fast light pulse can be slowed down experimentally after input into the nano-ring.

A soliton pulse is input and propagated within a micro-ring resonator, as shown in Figs 1(a) and 1(b), which consist of a series micro-ring resonators. The resonant output is formed; thus, the normalized output of the light field is the ratio between the output and input fields [$E_{out}(t)$ and $E_{in}(t)$] in each round-trip, which can be expressed as[5]

$$\left|\frac{E_{out}(t)}{E_{in}(t)}\right|^2 = (1-\gamma)\left\{1 - \frac{[1-(1-\gamma)x^2]\kappa}{\left[\begin{array}{c}(1-x\sqrt{1-\gamma}\sqrt{1-\kappa})^2\\ +4x\sqrt{1-\gamma}\sqrt{1-\kappa}\sin^2\left(\frac{\phi}{2}\right)\end{array}\right]}\right\}. \tag{3}$$

The closed form of Eq. (3) indicates that the ring resonator in this particular case is very similar to a Fabry-Pérot cavity, which has an input and output mirror with a field reflectivity, $(1-\kappa)$, and a fully reflecting mirror. 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. L and α are the waveguide length and linear absorption coefficient, respectively**.** In this work, the iterative method is introduced to obtain the results as shown in Eq. (3), similarly, when the output field is connected and input into the other ring resonators.

After the signals are multiplexed with the generated chaotic noise, then chaotic cancellation is required by the individual user. To retrieve the signals from the chaotic noise, we propose to use an add/drop device with the appropriate parameters. This is given in detail as follows. The optical circuits of ring resonator add/drop filters for the throughput and drop port can be given by Eqs. (4) and (5), respectively.[10]

$$\left|\frac{E_t}{E_{in}}\right|^2 = \frac{\left[\begin{array}{c}(1-\kappa_1) - 2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\exp\left(-\frac{\alpha}{2}L\right)\cos(k_n L)\\ +(1-\kappa_2)\exp(-\alpha L)\end{array}\right]}{\left[\begin{array}{c}1+(1-\kappa_1)(1-\kappa_2)\exp(-\alpha L)\\ -2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\exp\left(-\frac{\alpha}{2}L\right)\cos(k_n L)\end{array}\right]}, \tag{4}$$

$$\left|\frac{E_d}{E_{in}}\right|^2 = \frac{\kappa_1\kappa_2\exp\left(-\frac{\alpha}{2}L\right)}{\left[\begin{array}{c}1+(1-\kappa_1)(1-\kappa_2)\exp(-\alpha L)\\ -2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\exp\left(-\frac{\alpha}{2}L\right)\cos(k_n L)\end{array}\right]}, \tag{5}$$

where E_t and E_d represent the optical fields of the throughput and drop ports, respectively. $\beta=kn_{eff}$ is the propagation constant, n_{eff} is the effective refractive index of the waveguide, and the circumference of the ring is $L=2\pi R$, where R is the radius of the ring. In the following, new parameters will be used for simplification: $\phi=\beta L$ is the phase constant. The chaotic noise cancellation can be managed by using the specific parameters of the add/drop device, and the required signals can be retrieved by the specific users. κ_{61} and κ_{62} are coupling coefficients of the add/drop filters, $k_n=2\pi/\lambda$ is the wave propagation number for in a vacuum, and the waveguide (ring resonator) loss is $\alpha=0.5$ dBmm^{-1}. The fractional coupler intensity loss is $\gamma=0.1$. In the case of the add/drop device, the nonlinear refractive index is neglected.

3 Results and Discussion

In operation, the large bandwidth signal within the micro-ring device can be generated by using a common soliton pulse input into the nonlinear micro-ring resonator. This means that the broad spectrum of light can be generated after the soliton pulse is input into the ring resonator sys-

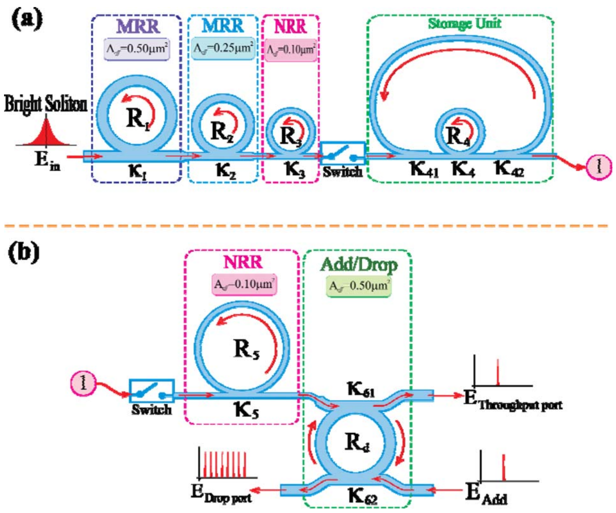

Fig. 1 A broadband source generation system; (a) a storage unit; (b) a soliton band selector, where R_s are ring radii, κ_s are coupling coefficients, κ_{41}, κ_{42} are coupling losses, and κ_{61} and κ_{62} are the add/drop coupling coefficients.

tem. The schematic diagram of the proposed system is as shown in Fig. 1. A soliton pulse with 50-ns pulse width and peak power at 2 W is input into the system. The suitable ring parameters are used, for instance, ring radii $R_1=15.0\ \mu$m, $R_2=10.0\ \mu$m, $R_3=R_s=5.0\ \mu$m, and $R_5=R_d=20.0\ \mu$m. In order to make the system associate with the practical device,[9] the selected parameters of the system are fixed to $\lambda_0=1.55$ mm, $n_0=3.34$ (InGaAsP/InP), $A_{eff}=0.50$, 0.25 μm^2 and 0.10 μm^2 for the micro-ring and nano-ring resonator, respectively, $\alpha=0.5$ dBmm^{-1}, and $\gamma=0.1$. The coupling coefficient (kappa, κ) of the micro-ring resonator ranged from 0.1 to 0.95. The nonlinear refractive index is $n_2=2.2\times10^{-13}$ m^2/W. In this case, the waveguide loss used is 0.5 dBmm^{-1}. The input soliton pulse is chopped (sliced) into the smaller signals spreading over the spectrum (i.e., broad wavelength), as shown in Fig. 2(b), which shows that the large bandwidth signal is generated within the first ring device.

In simulation, the coupling coefficients are given as shown in the figures. The coupling loss is included due to the different core effective areas between micro-ring and nano-ring devices, which are given by 0.1 dB. The obtained results have shown that a large bandwidth of the optical signals with the specific wavelength can be generated within the micro-ring resonator system. The amplified signals with broad spectrum can be generated, stored, and regenerated within the nano-waveguide, which is confirmed by Ref. 8. The maximum stored power of 10 W is obtained, as shown in Fig. 2(e), where the average regenerated optical output power of 4 W is achieved via the drop port of an add/drop filter, as shown in Figs. 2(h)–2(k), which is a broad spectra of light covering the large bandwidth, as shown in Fig. 2(g). However, to make the system realistic, the waveguide and connection losses must be addressed in the practical device, which may be affected by the signal amplification. In applications, the increase in communication channel and network capacity can be formed by using the different soliton bands (center wavelength), as shown in Fig. 2, where 2(h) 0.51 μm, 2(i) 0.98 μm, 2(j) 1.48 μm, and 2(k) 2.46 μm are the generated center wavelengths of the soliton bands. The selected wavelength center can be created by using the designed add/drop filter, whereby the required full width at half maximum (FWHM) and free spectral range (FSR) are obtained. In operation, the channel spacing and bandwidth are represented by FSR and FWHM, respectively—for instance, the FSR and FWHM of 2.3 nm and 100 pm are obtained, as shown in Fig. 2(i).

To verify the design system, we present one of the results that have been investigated in the laboratory. In fact, the same reason of pumped soliton and Gaussian soliton generation as the intense input light is required in the operating system, where there are two methods that can be used to perform the experiment: (1) using a high-power light source, and (2) reducing the media length, i.e., ring radius. An experimental setup of the multisoliton generation is shown in Fig. 3. The system consists of an erbium-doped fiber amplifier (EDFA), a semiconductor optical amplifier (SOA), a fiber ring resonator, and a 90:10 output coupler. The EDFA was constructed by using a 5-m length of erbium-doped fiber (EDF), with erbium concentration of 950 ppm. The EDF is pumped by a 980-nm laser diode (LD) at a pumped power of 66.0 mW. A wavelength division multiplexer (WDM) is used to combine the pump and laser wavelength. An SOA is incorporated in the ring cavity to amplify the signal from the EDFA. A ring resonator was constructed by using a 3-dB coupler. A polarization controller (PC) and 3-m length of polarization maintaining fiber (PMF) are included within the system. The principle of the ring resonator is related to the interferometer configuration, in which there are four port optical couplers with two inputs and two outputs with 50:50 splitting ratio. The light beam is split into two beams, of which one propagates a round the fiber ring, whereas the other propagates through the straight fiber. One of the beam polarization states is adjusted by using a PC within the fiber ring, and this produces a slicing effect, whereby the intensity is dependent on the interference of the two beams at the PMF. The change in fiber birefringence affects the change in fiber refractive index. The multisoliton band can be generated by adjusting the fiber ring radius and the birefringence, whereby the modulation signals, i.e., multisoliton pulses, can be observed over the base band signals, as shown in Fig. 4. A 90:10 output coupler is used to tap the output of the ring cavity laser. The output signal is characterized using an ANRITSU optical spectrum analyzer (OSA) with resolution of 50 pm. Figure 4(a) shows the lasing of the hybrid configuration in a ring cavity. The multisoliton pulses have seven channels with 16-nm bandwidth and with constant channel spacing. The maximum output power is 5.20 dBm. The fluctuations of the channels are less than 3 dB except for the third channel. The four-wave mixing also contributes to this fluctuation. The tunable output is obtained by coupling the coefficient variation, as shown in Fig. 4(b).

4 Conclusion

We have proposed very interesting results where multisoliton bands can be generated by using a common soliton wavelength propagating within a nonlinear waveguide system. The device parameters have been designed closely to

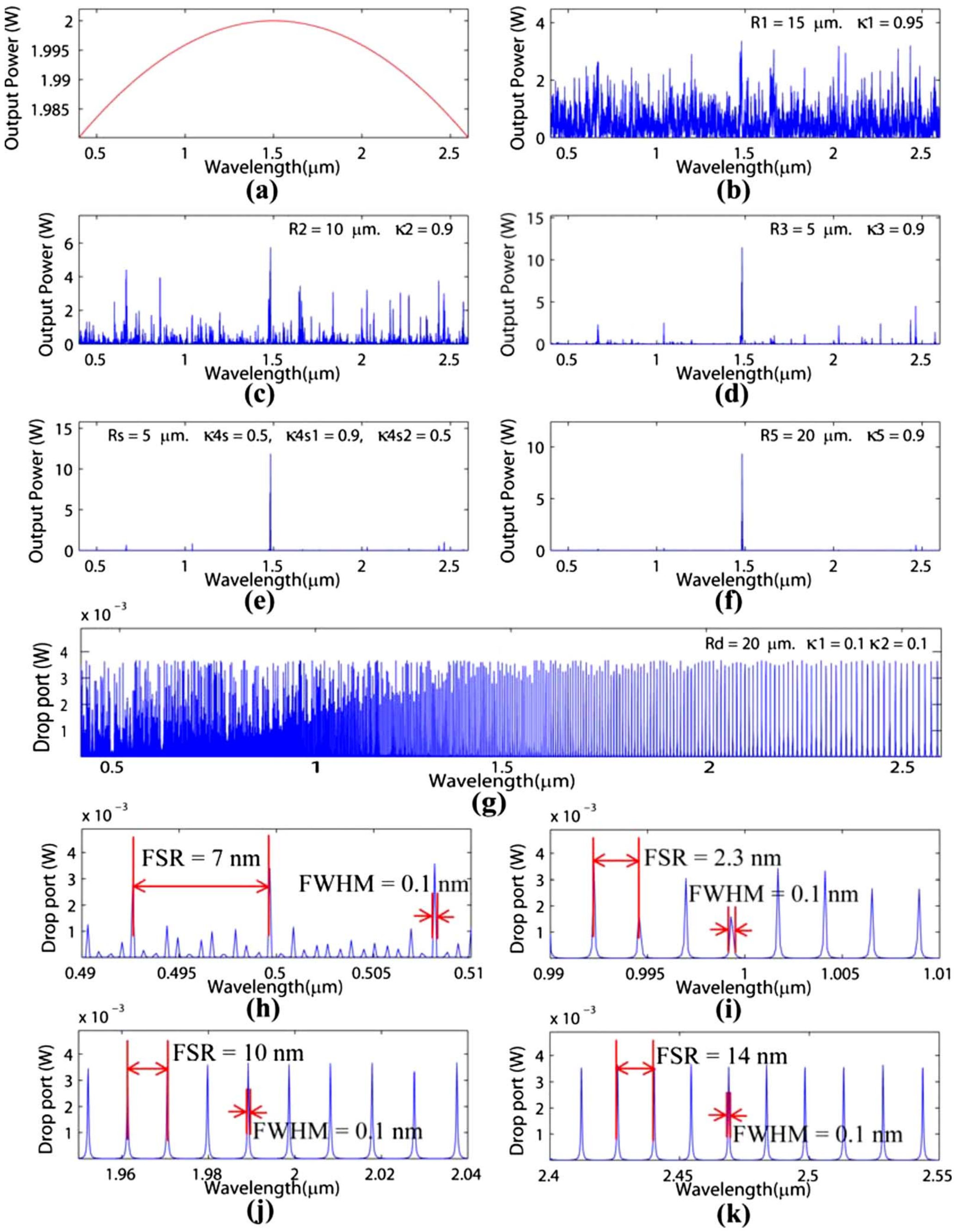

Fig. 2 A soliton band with center wavelength at 1.99 μm; (a) input soliton, (b) ring R_1, (c) ring R_2, (d) ring R_3, (e) storage ring, (R_s), (f) ring R_5, and (g), (h), (i), (j), and (k) drop port signals.

the practical values, which can be fabricated within a single system. In applications, the large bandwidth of the soliton bands can provide for large user demand-in the future; however, in practice, the problem of soliton collision within the device must be resolved, which is well analyzed by Ref. 5. The parameters that can be used to control the required free spectral range and spectral width (i.e., bandwidth) are the main parameters, where the soliton cross talk and collision are managed. In practice, the drop port output can be controlled by the ring radius and coupling coefficient of the add/drop filter. Therefore, by using the same level of input power into the add/drop filter, the power of the drop port

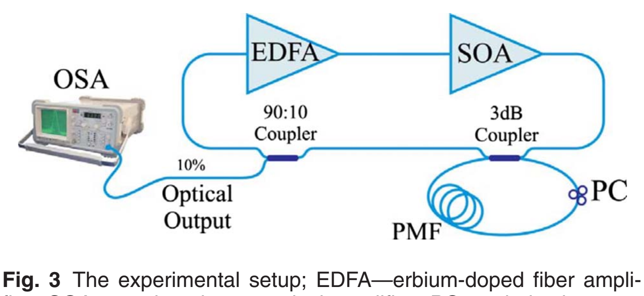

Fig. 3 The experimental setup; EDFA—erbium-doped fiber amplifier; SOA—semiconductor optical amplifier; PC—polarization controller; PMF—polarization maintaining fiber.

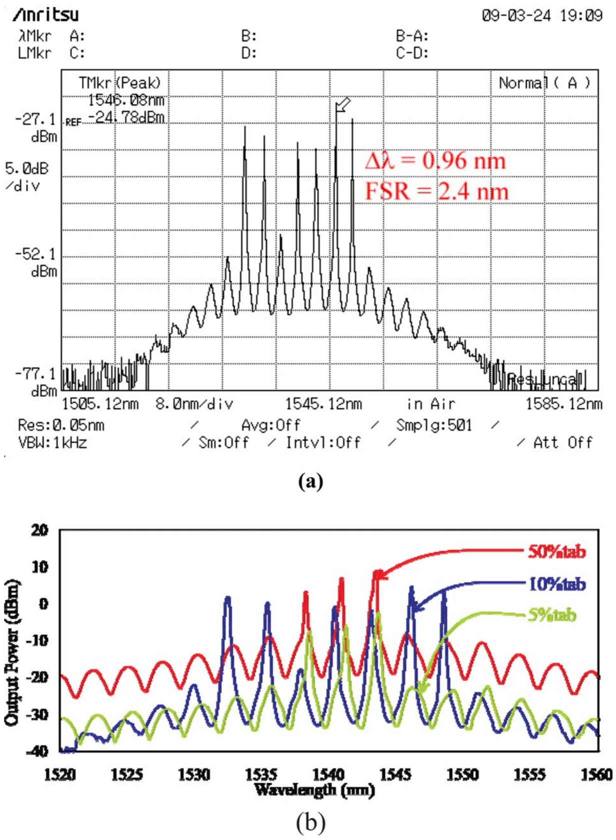

Fig. 4 Result of a multisoliton band with center wavelength at 1.54 μm, where (a) is single output and (b) is tunable output.

can be kept constant. The best results of FSR and FWHM obtained are 14 nm and 100 pm, respectively, which allows an increase in channel capacity of at least 10 times in only one center wavelength. This means that the idea of a personal wavelength (network) is realistic for large user demand due to unlimited wavelength discrepancy, whereby a specific soliton band can be generated using the proposed system. Apart from communication applications, potentially of broad soliton bands such as visible soliton (color soliton), UV-soliton, x-ray soliton, and infrared soliton can be generated and used for applications such as multicolor holography, medical tools, security imaging, and transparent holography and detection.

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Jalil Ali received his PhD in plasma physics from Universiti Teknologi Malaysia (UTM) in 1990. At present, he is a professor of photonics at the Institute of Advanced Photonics Science, UTM. He has authored/co-authored more than 60 technical papers published in international journals and two books. His area of interests are in FBGs, optical solitons, fiber couplers, and nanowaveguides. He is currently the Director for Innovation and Consultancy of UTM. Dr. Jalil Ali is a member of OSA, SPIE, and the Malaysian Institute of Physics.

Khuntong Sarapat received his BSc and MSc in physics and applied physics from Khon Kaen University, Thailand, in 2003, and from King Mongkut's Institute of Technology Ladkrabang, Bangkok, in 2009, respectively. He is currently a PhD student in physics in the Department of Physics, Faculty of Science, University of Technology Malaysia, Johor Bahru, and a member of the department research staff. His research interests are nonlinear optics, nonlinear communication, nnano-waveguides, and quantum information.

Preecha P. Yupapin received his PhD in electrical engineering from City University, London, in 1993. He is a professor in applied physics in the Applied Physics Division, Faculty of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok, He has authored/co-authored 130 international scientific index journal papers and eight books. His research interests are in optical sensors, nanophotonics, linear and nonlinear optical communication, quantum information, and nano-waveguide design. Professor Yupapin is a member of the Thai Institute of Physics (TIP) and SPIE and has been president of the Optical Society of America, Thailand Chapter (OSA-Thailand) since 2002. He has been the head of the Applied Physics Division since October 2008.