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Fast and slow light generation using chaotic signals in nonlinear microring resonators for communication security

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Abstract. We propose a new system of signal security using nonlinear micro ring resonators for optical communication system. When a soliton pulse is input into the system, the chaotic signal is generated and multiplexed into the optical link. The chaotic waveform can be canceled using an add/drop device connected into the transmission link. Using the appropriate ring parameters, the original signal can be retrieved. An other application results from the fact that the fast and slow light behaviors can be presented, and can be seen using the add/drop multiplexers. In some cases, we can generate signal to obtain the two identical "signal" and "ghost" signals, which are observed in a different time frame. In this application, communication security can be performed when the required information is multiplexed and performs the link using the chaotic signal, fast and slow light, and signal and ghost signals, where the original signal can be retrieved by the known clients. [DOI: 10.1117/1.3065515]

Subject terms: communication security; fast and slow lights; ghost and signal generation; optical communication.

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1 Introduction

An optical ring resonator has become a promising device for optical signal processing applications, where the nonlinear behavior of light traveling within the device has been widely investigated.[1–3] Ferreira described the nonlinear behavior of light within an optical fiber,[4] where the nonlinear properties of light including soliton pulses have been described. The use of a microring device to form the nonlinear behaviors with various applications has been proposed.[5,6] Using the nonlinear behavior of light for communication security has long been one of the popular research areas in communication. The key point is that a system with perfect security is necessary in a realistic application. Several signal security techniques such as digital encoding,[7] chaotic noise generation and cancellation,[8] chaotic encoding,[9] quantum chaotic encoding,[10] and quantum encoding[11] have been proposed. More details of such techniques are also described in Ref. 12. In principle, the quantum technique is recommended to achieve perfect security, however, a problem remains due to the difficulty of implementation. Until now, no dominant technique has been used for communication security. The search for such a technique that serve both security requirements and a realistic system continues. Recently, Yupapin et al.[12] reported an interesting results when an ultrafast pulse with pulse widths in attoseconds (as) can be easily generated using a soliton pulse traveling in nonlinear microring resonators (NMRRs). The interesting idea is that the system is very small, making it possible to implement within a communication device and system. The device fabrication at such a scale is confirmed by Ref. 13. In this paper, we propose a system that can be used to generate fast and slow light behavior and the signal and ghost concept. First, the chaotic signal is generated within a nonlinear microring device and can be canceled using the designed add/drop multiplexer. Second, we propose the concept of fast and slow light, where fast light in the form of a soliton pulse can perform the signal in a slower time frame, which can be detected using the add/drop multiplexer. In some cases, it is found that there are two identical signals with different time frames, i.e., the signal and ghost. Using this scheme, a pair of the same signals is generated and separated by the certain time interval, where one signal is in front and called the signal and the other is behind and is called the ghost. Both signals are generated by using a soliton pulse input into a nonlinear microring resonator. The involved parameters are ring radius, coupling coefficient, and refractive index. In principle, when the signal transmission is in the network, the control parameters are known by the specific clients. Obtained results have shown that the optical power left after dropping is still valid for a long-distance link. In application, we can use the proposed system to form the communication security system, where the chaotic noise, fast and slow light, and signal and ghost can be easily generated and retrieved by the specified users.

2 Operating Principle

The optical soliton is recognized[14] as a powerful laser pulse that can be used to generate the chaotic filter characteristics when it propagates within NMRRs.[14] When the soliton

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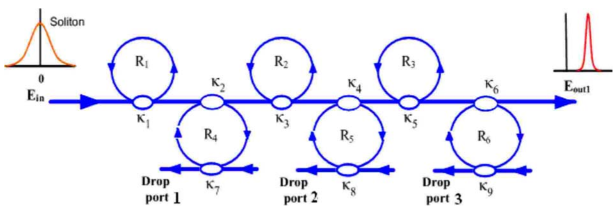

Fig. 1 Schematic diagram of microring devices and add/drop multiplexers in the communication link.

pulse is introduced into the multistage microring resonators, as shown in Fig. 1, the input optical field (E_n) in the form of a soliton pulse is expressed by.

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

where A and z are the optical field amplitude and propagation distance, respectively; T is a soliton pulse propagation time in a frame moving at the group velocity; $T = t\text{-}\beta_1(z)$, where β_1 and β_2 are the coefficients of the linear and second-order terms of Taylor expansion of the propagation constant; and $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse. The frequency shift of the soliton is ω_0. This solution describes a pulse that maintains 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_0 is known. For the soliton pulse in the microring device, a balance should be achieved between the dispersion length (L_D) and the nonlinear length $[L_{\text{NL}} = (1/\Gamma\phi_{\text{NL}})]$, where $\Gamma = n_2 k_0$, is the length scale over which dispersive or nonlinear effects cause the beam to become wider or narrower. For a soliton pulse, there is a balance between dispersion and nonlinear lengths, hence, $L_D = L_{\text{NL}}$.

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

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

where n_0 and n_2 are the linear and nonlinear refractive indices, respectively; and 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 microring and nanoring resonators, the effective mode core areas range[13] from 0.50 to 0.1 μm^2.

When a soliton pulse is input and propagated within a microring resonator, as shown in Fig. 1, which consists of a series microring resonators, the resonant output is formed. Thus, the normalized output of the light field is the ratio between the output and input fields $[E_{\text{out}}(t)$ and $E_{\text{in}}(t)]$ in each roundtrip, which can be expressed as

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

The closed form of Eq. (3) indicates that a 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-κ) and a fully reflecting mirror. Here κ is the coupling coefficient; $x = \exp(-\alpha L/2)$ represents a roundtrip loss coefficient; $\phi_0 = kLn_0$ and $\phi_{\text{NL}} = kLn_2|E_{\text{in}}|^2$ are the linear and nonlinear phase shifts; and $k = 2\pi/\lambda$ is the wave propagation number in a vacuum, where L and α are a waveguide length and linear absorption coefficient, respectively. In this paper, the iterative method is introduced to obtain the results, as shown in Eq. (3); and similarly, when the output field is connected and input into the other ring resonators.

The input optical field, as shown in Eq. (1), i.e., a soliton pulse, is input into an NMRR. Using the appropriate parameters, the chaotic signal is obtained using Eq. (3). To retrieve the signals from the chaotic noise, we propose to use the add/drop device with the appropriate parameters. This is given in detail as follows. The two complementary optical circuits of ring resonator add/drop filters can be given by[14]

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

and

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

where E_t and E_d represent the optical fields of the throughput and drop ports respectively; κ_1 and κ_2 are coupling coefficients; $\beta = kn_{\text{eff}}$ 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 are 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, for which the required signals can be retrieved by specific users. Here κ_1 and κ_2 are coupling coefficients of add/drop filters, $k_n = 2\pi/\lambda$ is the wave propagation number in a vacuum; and the waveguide (ring resonator) loss is $\alpha = 0.5\ \text{dB mm}^{-1}$. The fractional coupler intensity loss is $\gamma = 0.1$. In the case of add/drop device, the nonlinear refractive index is neglected.

In operation, as shown in Fig. 1, the proposed system can be used to generate the chaotic signal by using the first microring resonator, and the cancellation of the chaotic sig-

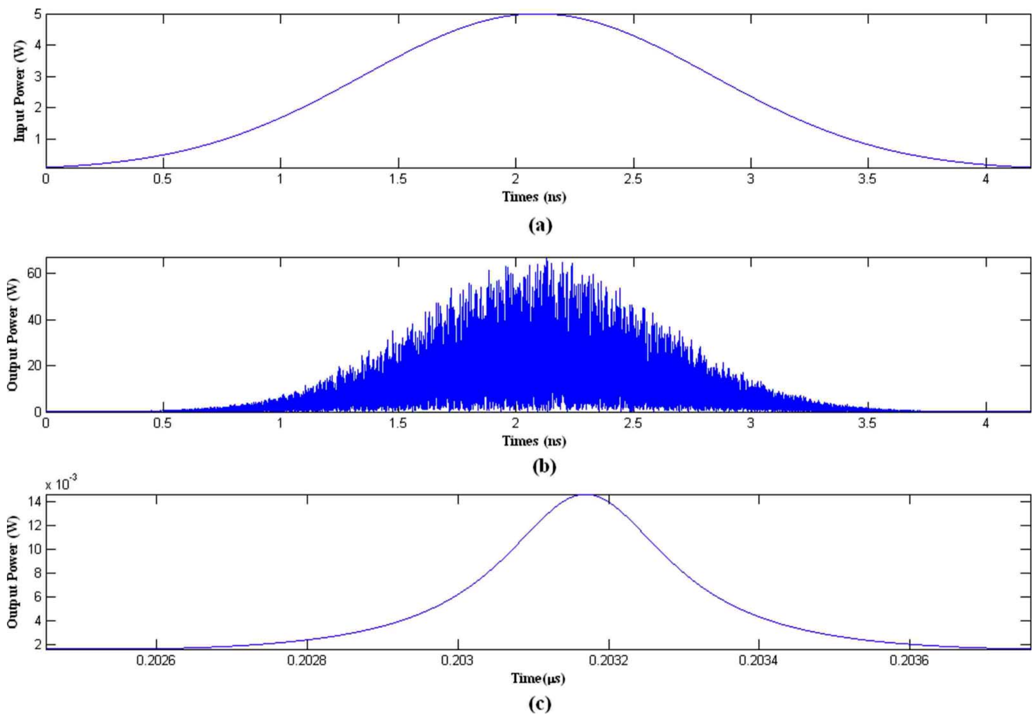

Fig. 2 Chaotic and filter signals obtained at R_1 and R_4, respectively: (a) input signal (fast light), (b) chaotic signal, and (c) drop port signal (slow light).

nal can be achieved by using the add/drop filter (multiplexer) with the appropriate parameters. To obtain more power, which is suitable for a long-distance link, the soliton pulse is recommended for chaotic signal generation. The chaotic signal cancellation can be obtained by using the add/drop filters at drop ports 1, 2, and 3 of the add/drop filters R_4, R_5 and R_6.

3 Results and Discussion

When the optical power in the form of a soliton pulse is input into the first ring of the system as shown in Fig. 1, nonlinear behavior occurs, which is induced the noisy signal called chaotic signals. In this case, an optical power of 5 W is input into the first microring device, where the other parameters are $\lambda_0=1.55$ μm, $n_0=3.34$, and $A_{\text{eff}}=0.25$ μm^2. The waveguide ring resonator loss is $\alpha=0.5$ dB mm^{-1}. The practical bending loss of the waveguide fabricated by InGaAsP/InP is confirmed by Yupapin and Suwancharoen,[7] and the propagation loss is as low as 1.3 ± 0.02 dB mm^{-1} at 1.55 μm. The fractional coupler intensity loss is $\gamma=0.1$, and $R_1=R_2=R_3=10$ μm. The nonlinear refractive index used is $n_2=2.2\times10^{-17}$ m^2 W^{-1}, and the data used has 20,000 iterations, which is approximately equal to 29×10^{-12} s (29 ps). We assume that $\phi_L=0$ for simplicity; however, the change in phase slightly altered the optical output, which means the dispersion can be neglected when the resonant output occurs. After the 5-W soliton pulse at time $T_0=5$ ns is input into the first ring, as shown in Fig. 2(a), the chaotic signal is generated as shown in Fig. 2(b). The coupling coefficient κ_1 is 0.5. The chaotic cancellation is obtained by using the add/drop filter at drop port 1, as shown in Fig. 2(c), when $\kappa_2=\kappa_7=0.3$ and ring resonator radius $R_4=12$ μm. The drop signal obtained is slower in time than the original input signal, which can be called fast (input) and slow (output) light behaviors. From this result, it is confirmed that the remaining optical power is available for long-distance link.

Figure 3 shows the output signals at the drop ports of R_4, R_5, and R_6. There are two forms of the signals: one obtained by the bandstop filter and the other by the bandpass filter. Where the ring radius $R_4=15$ μm, and the coupling coefficient $\kappa_2=\kappa_7=0.1$, as shown in Fig. 3(a). There are identical signals with a separation time of 18 ns. We call these two signals as ghost and signal for faster and slower in times, respectively. Figure 3(b) shows the output signal

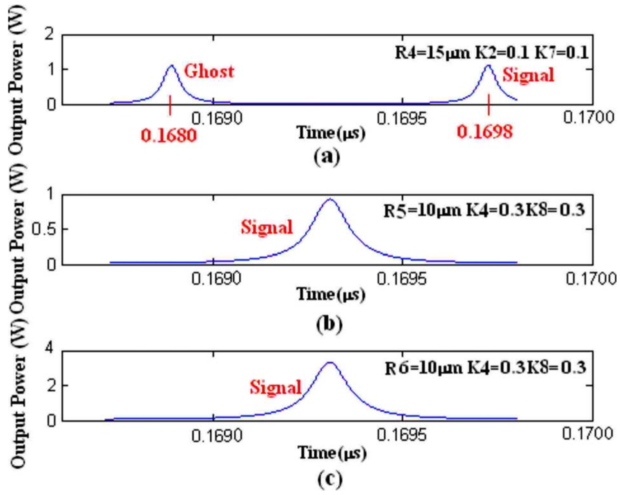

Fig. 3 Output signals obtained at drop port R_4, R_5, and R_6: (a) ghost and signal, (b) signal, and (c) signal.

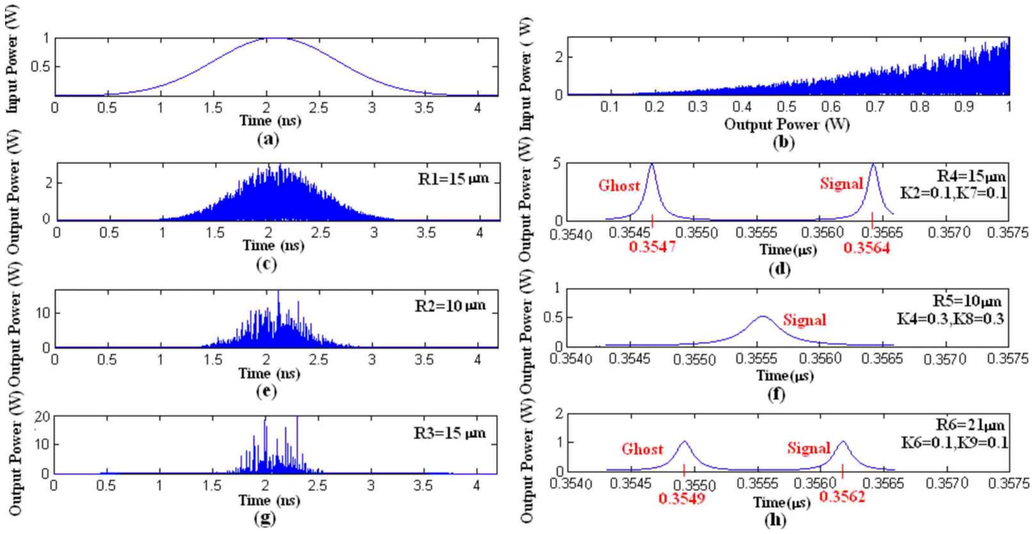

Fig. 4 Chaotic signals generated by R_1, R_2, and R_3 and the output signals at drop ports R_4, R_5, and R_6: (a) input signal, (b) input and output power, (c) chaotic signal, (d) ghost and signal, (e) chaotic signal, (f) drop port signal, (g) chaotic signal, and (h) ghost and signal.

obtained when $\kappa_4=\kappa_8=0.3$ and the ring radius (R_5) is 10 μm. Figure 3(c) shows the signal after the cancellation (i.e., bandpass filter) with the parameters $R_6=10$ μm and coupling coefficients $\kappa_4=\kappa_8=0.3$.

Figure 4(a) shows the input power waveform with a center peak at 2 ns, and Fig. 4(b) shows the relationship between the input and output power. The slower chaotic signals are seen in Figs. 4(c), 4(e), and 4(g), and the corresponding drop port signals are shown in Figs. 4(d), 4(f), and 4(h). The parameters used are $R_1=R_3=R_4=15$ μm, $R_2=R_5=10$ μm, $R_6=21$ μm, $\kappa_2=\kappa_7=0.1$, $\kappa_4=\kappa_8=0.3$, and $\kappa_6=\kappa_9=0.1$. The bandstop filter signals are obtained in Figs. 4(d) and 4(h), and the bandpass filter signal with a slower time (in microseconds) is obtained in Fig. 4(f). Separation times of the ghost and signal of 1.7 and 1.3 ns are obtained in Figs. 4(d) and 4(h), respectively.

In applications, communication security can be performed in networks. Using the proposed system, the chaotic signals can be generated and transmitted into the optical communication link, and the specified users along the networks who know the correct details of the add/drop device can retrieve the required information. However, there are two schemes in the proposed system. First, the chaotic cancellation can be made by using the fast and slow light method. Second, a pair of signal and ghost signals can be used for confirmation using the specified separation time. In practice, two key points of this application are the secret parameters, and the proposed device is now being fabricated and available, and will be implemented in the near future.

4 Conclusion

We proposed the use of chaotic signals within a microring resonator for communication security, where the required communication signals can be formed and submerged within the noisy signals. They can be used to form the security signals using a soliton pulse in the NMRRs. Secure information with sufficient coupling power via a soliton pulse within an NMRR can be used to perform communication security for long-distance links. We proposed two techniques, one called fast and slow light and the other called ghost and signal generation. These two techniques can be used to form signal security, whereas the required end-users can retrieve the signals using the corrected device and scheme. Using this proposed scheme, communication security can be employed by incorporating the transmission data in the communication system. Therefore, the communication security requirement is plausible. The advantage of the system is that a clear signal can be retrieved by the specific add/drop filter design, which is now commercially made.

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