GHz frequency band soliton generation using integrated ring resonator for WiMAX optical communication

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Abstract New system of optical soliton signal generation with a high frequency band is presented. Microring resonator can be used to generate soliton signals with high frequency of GHz. These signals can be transmitted via a wireless network system known as WiMAX, which is providing broadband wireless access up to 50 km. The soliton pulses are more stable with less loss during propagation which is good candidate compare to other current optical waves used in optical communication. In this study, soliton pulses with full width at half maximum of 3 MHz and FSR of 85 MHz could be generated using an add/drop filter system which is used to generate high frequency signals, required for wireless network systems. These pulses can be used as carrier signals in order to transmit information codes without significant changes, thus improving transmission quality and delivery of the right information.

Keywords WiMAX network system · Optical soliton · Add/drop filter system · High frequency band

1 Introduction

A wireless digital communications system known as WiMAX is providing broadband wireless access (BWA) up to 50 km for fixed stations, and 5–15 km for mobile stations (Xiong et al. 2011; Ghosh et al. 2005). Therefore WiMAX is a communication technology for wirelessly delivering high-speed Internet service to large geographical areas. In contrast, the WiFi wireless local area network standard is limited in most cases to only 30–100 m (Callaway et al. 2002; Ala-Laurila et al. 2001). WiMAX becomes more and more popular every day

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(Vaughan-Nichols 2004; Sidhu et al. 2007). This technology can be expressed as a combination of Global System for Mobile (GSM) and WiFi (Kang et al. 2012; Kumar et al. 2012). It inhabits cellular structure from GSM and modified data transfer protocols from WiFi (Yen et al. 2011). WiMAX can be used for wireless networking as the more common WiFi protocol (Robertazzi 2012). Therefore, WiMAX allows for more efficient bandwidth use, interference avoidance allowing higher data rates over longer distances and will be a very well recognized term to describe wireless Internet access throughout the world (Mardini et al. 2011; Chamodrakas and Martakos 2012; Huang et al. 2012).

WiMAX can be used with a range of devices to connect to the Internet, such as laptops, mobile, smart or VoIP phones, personal digital assistants (PDA), Global Positioning System (GPS) navigation devices, or video surveillance cameras (Huang et al. 2010; Celandroni et al. 2013; Mujyambere 2012). The Fixed towers which are connected with home or office subscriber units, such as a WiMAX ISP provided indoor or outdoor subscriber unit operates on high power output transmissions preparing 3.5 GHz signals out to distances of 25 miles (Wong et al. 2009). Mobile towers operate entirely different than fixed towers due to handheld devices being limited on battery and processing power. IEEE 802.16d will connect with fixed towers, and IEEE 802.16e equipment connects and operates on Mobile towers (Eiselt and Marianov 2012). The WiMAX wireless Internet solution is a very ingenious network topology of mixed telecommunication towers (Liu and Chen 2012; Kang et al. 2012; Palmeira and de Oliveira Duarte 2012). The tower array not only allows for fixed and mobile communications between the subscriber and ISP, but even supports roaming between ISP networks contributing to the term WiMAX Interoperability (Park 2006).

The advantages of WiMAX such as technology features spectral efficiency, advanced antenna technologies, open standards, cost advantages, and flat IP architecture, which new entrants can be used to bridge the digital divide, provide next generation mobile broadband applications (Yates and Lehr 2012; Raychaudhuri and Mandayam 2012). The current technology of the WiMAX network has a lack of quality service due to not supporting many users at the same tower which leads to having heavy traffic and difficulties to maintain high quality (Hu et al. 2011).

Moreover, the quality of services decreases in rainy season because the weather condition could interrupt the signal, which may cause of bad signal and broadcasting may be stopped or interrupted, therefore high capacity of transferring signals with high power are required to solve this problem. The use of smart antenna in WiMAX network offering high quality widest array, which is enable to make possible communication without any encryption, where, it offers 2.3, 2.7, and 3.3, 3.8 GHz frequency ranges (Tam et al. 2012; Abalenkovs 2012). In the case of security, WiMAX technology offers very high security because of encryption system used by this system which can be improved by employing novel ring resonators to generate soliton signal's frequency in wide ranges of Hz (Vissers et al. 2012). The increased range is due to the frequencies used and the power of the transmitter, where at that distance, terrain, weather and large buildings will act to reduce the maximum range in some circumstances, but the potential is there to cover huge tracts of land. This technology supports both wireless and wired networks including cable operator.

Multi soliton generation becomes an interesting subject when it is used to enlarge the capacity of communication channels (Teeka et al. 2011; Amiri and Ali 2013c; Afroozeh et al. 2010, 2011). The high optical output of the ring resonator system is of benefit to long distance communication links (Amiri et al. 2013d,h; Afroozeh et al. 2012b). Dense wavelength of optical pulses can be generated when the soliton pulse is propagated within the nonlinear MRR system and produce large bandwidth of signals offered for quantum dense coding and quantum packet switching applications (Amiri et al. 2011, 2012f). The use

of quantum codes has been proposed in many research works, while the applications such as long distance, optical wireless, satellite, have been detailed (Mishmash and Carr 2007; Amiri et al. 2013i,j; Kouhnavard et al. 2010). Nevertheless, a new reliable system for wireless system is needed, which has both high capacity and secure tools (Amiri et al. 2012o). Amiri et al. have projected the use of multi soliton pulses applied in a network system, where, a nonlinear MRR system is used to form the multi wavelength signals (Amiri and Ali 2013a,e; Amiri et al. 2011a).

A wireless access system transmits data to different users via wireless connection (Nikoukar et al. 2012; Shahidinejad et al. 2014). The transmission of information can be sent to the Internet using a physical, wired Ethernet connection (Xu and Lu 2013). This method also works in reverse, when the router system used to receive information from the Internet, translating it into an analog signal and sending it to the computer's wireless adapter (Sun et al. 2012; Gong et al. 2013). Internet security has become an important function in the modern internet service. However, the security technique known as quantum cryptography has been widely used and investigated in many applications, using optical tweezers (Palima and Glückstad 2012; Mora et al. 2012).

Amiri et al. proposed an add/drop optical filter system to increase the capacity of the MRR system (Amiri et al. 2011b, 2012d). By using the proposed system, the transceiver can be integrated and operated using a single device. One important aspect of the system is that the required soliton pulses with specific key parameters such as finesse can be obtained at the drop/through ports of the system by tuning the parameters of the system.

The advantage of the proposed system is that the transmitter can be fabricated on-chip, or operated alternately by a single device (Amiri et al. 2013g). Although, at present, laser sources have faced limited market acceptance due to shortcomings such as a limited tunability range and cumbersome size, these constraints are rapidly disappearing with the invention of new classes of tunable diode laser setups. Reliability, compactness and efficiency are among the major advantages of these new lasers. Exciting new technological progress, particularly in the field of tunable narrow band laser systems, multiple transmission and the microring resonator systems, provides the foundation for the development of new transmission techniques in wireless communication systems (Shahidinejad et al. 2012; Amiri et al. 2013e). Besides improvements in efficiency and beam quality, these soliton sources provide better sensitivity required for sensing systems, leading to improved process efficiencies and new fields of optical sensors. The soliton pulses are so stable that the shape and velocity are preserved while travelling along the medium

2 Theoretical modeling

Optical soliton is a powerful laser pulse used to expand the optical bandwidth, while it propagates within the nonlinear MRR (Teeka et al. 2011; Yupapin et al. 2010). Additionally, the large output gain is obtained by the soliton self-phase modulation (Dai et al. 2012; Zang and Yang 2011; Zang and Zhang 2012). The system of GHz frequency band generation is presented shown in Fig. 1.

Optical fields of bright soliton pulse can be inserted into the input port of the multi-stage MRR's system expressed by (Amiri et al. 2012e; Sadegh Amiri et al. 2013)

$$E_{in}(t, z) = A \sec h \left[\frac{T}{T_0} \right] \exp \left[\left(\frac{z}{2L_D} \right) - i\omega_0 t \right] \tag{1}$$
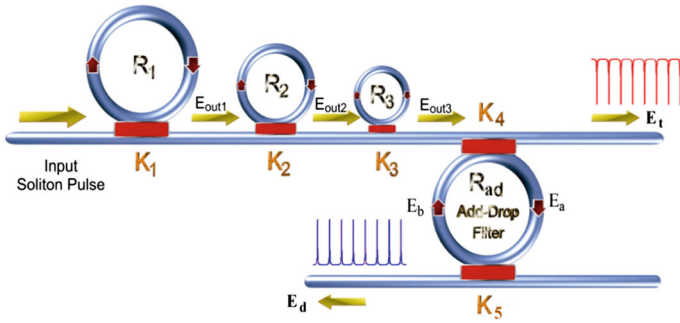
Fig. 1 A schematic of the proposed MRR's system, where Rs: ring radii, κ_s: coupling coefficients, R_{ad}: an add/drop ring radius for multi GHz soliton pulse generation

where A is the amplitude of optical fields and z is the distance of propagation, respectively, where t is the soliton phase shift time, and the carrier frequency of the signal is ω_0 (Amiri et al. 2012n,i, 2013f). T is the required time of a soliton pulse to propagate (Gifany et al. 2013). The dispersion length of the soliton pulse is described by $L_D = T_0^2 / |\beta_2|$ where β_2 is a propagation constant (Amiri et al. 2012l). Optical beams have an internal tendency to spread as they propagate in a homogeneous medium. An optical waveguide is an important device to present a balance between chromatic dispersion and phase shift modulation where the medium is uniform in the direction of propagation (Amiri and Ali 2013d, 2014a; Amiri et al. 2013a). In the microring device, a balance should be achieved between the dispersion length (L_D) and the nonlinear length (L_{NL}) for the temporal soliton pulse, while the spatial soliton can be formed when the balance is between the diffraction and the nonlinear effect (Amiri et al. 2012k). The nonlinear length can be described by the relation ($L_{NL} = 1/\gamma\phi_{NL}$), where γ and ϕ_{NL} are coupling loss of the field amplitude and nonlinear phase shift, respectively (Amiri et al. 2012j). The refractive index of the medium varies while propagating, thus creating a structure similar to a graded-index fiber. The refractive index of a nonlinear optical fiber ring resonator is following the Kerr-type, so it can be given by (Amiri et al. 2012g)

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

where n_o and n_2 are the linear and nonlinear refractive indexes, respectively. I and P are the optical intensity and optical power, respectively (Amiri et al. 2012a). A_{eff} is representing the effective mode core area of the device (Nikoukar et al. 2011). The resonant output is formed when a soliton pulse is input and propagated within the MRRs. Therefore, the normalized output of the light field which is the ratio between the output and input fields $E_{out}(t)$ and $E_{in}(t)$ for each round-trip of a single ring resonator, can be expressed by (Amiri et al. 2012c; Amiri and Ali 2013f, 2014b,c)

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

In Eq. (3), κ is the coupling coefficient, and $x = \exp(-\alpha L/2)$ represents a round-trip loss coefficient (Alavi et al. 2013; Afroozeh et al. 2012a), where the waveguide length and linear absorption coefficient are given by L and α, respectively (Jalil et al. 2011). $\phi = kLn_0$ and

$\phi_{NL} = kLn_2|E_{in}|^2$ are the linear and nonlinear phase shifts. Wave propagation number in a vacuum is given by $k = 2\pi/\lambda$ (Amiri et al. 2012m; Amiri and Ali 2013c). Therefore, the iteration method is used to achieve the results when the output field from each ring resonator is launched into the next ring resonators shown in Eq. (3). Bright soliton pulse described by Eq. (1) is input into a nonlinear MRRs, where the chaotic signal can be formed. To retrieve the signals from the chaotic noise, Amiri et al. suggested to utilize an add/drop device with suitable parameters (Amiri et al. 2011c, 2012h). For the add/drop system, the interior electric fields (E_a and E_b) can be expressed by (Amiri and Ali 2012, 2013b; Amiri et al. 2013a),

$$E_a = E_{out3} \times j\sqrt{\kappa_4} + E_b\sqrt{1-\kappa_4}e^{\frac{-\alpha}{2}\frac{L}{2}-jkn\frac{L}{2}} \tag{4}$$

$$E_b = E_a\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}} \tag{5}$$

Thus,

$$E_a = \frac{E_{out3} \times j\sqrt{\kappa_4}}{1 - \sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL}} \tag{6}$$

$$E_b = \frac{E_{out3} \times j\sqrt{\kappa_4}}{1 - \sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL}} \cdot \sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}} \tag{7}$$

where κ_4 and κ_5 are the coupling coefficients, $L = 2\pi R$, and R is the radius of the add/drop system. The throughput and drop port electrical fields of the add/drop system can be expressed by:

$$E_t = E_b e^{\frac{-\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}}j\sqrt{\kappa_4} + E_{out3} \times \sqrt{1-\kappa_4} \tag{8}$$

$$E_d = E_a e^{\frac{-\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}}j\sqrt{\kappa_5} \tag{9}$$

Thus,

$$\frac{E_t}{E_{out3}} = \frac{-\kappa_{41}\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL} + \sqrt{1-\kappa_4} - (1-\kappa_{41})\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL}}{1 - \sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL}}$$

$$= \frac{-\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL} + \sqrt{1-\kappa_4}}{1 - \sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL}} \tag{10}$$

$$\frac{E_d}{E_{out3}} = \frac{-\sqrt{\kappa_4 \cdot \kappa_5}e^{\frac{-\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}}}{1 - \sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{\frac{-\alpha}{2}L-jk_nL}} \tag{11}$$

The normalized intensity outputs of a ring resonator add/drop filter system can be expressed by Eqs. (12) and (13).

$$\frac{|E_t|^2}{|E_{out3}|^2} = \frac{(1-\kappa_4) - 2\sqrt{1-\kappa_4} \cdot \sqrt{1-\kappa_5}e^{-\frac{\alpha}{2}L}\cos(k_nL) + (1-\kappa_5)e^{-\alpha L}}{1 + (1-\kappa_4)(1-\kappa_5)e^{-\alpha L} - 2\sqrt{1-\kappa_4} \cdot \sqrt{1-\kappa_5}e^{-\frac{\alpha}{2}L}\cos(k_nL)} \tag{12}$$

$$\frac{|E_d|^2}{|E_{out3}|^2} = \frac{\kappa_4\kappa_5 e^{-\frac{\alpha}{2}L}}{1 + (1-\kappa_4)(1-\kappa_5)e^{-\alpha L} - 2\sqrt{1-\kappa_4} \cdot \sqrt{1-\kappa_5}e^{-\frac{\alpha}{2}L}\cos(k_nL)} \tag{13}$$

where E_t and E_d are the optical outputs of the through and drop ports, respectively, while the output power from the third ring of the MRR's system is shown by E_{out3}. The propagation constant is given by $\beta = kn_{eff}$, where the effective refractive index of the waveguide is represented by n_{eff} (Amiri et al. 2012b). By using particular parameters of the add/drop device, the chaotic noise cancellation can be performed (Amiri et al. 2012p). The micro ring
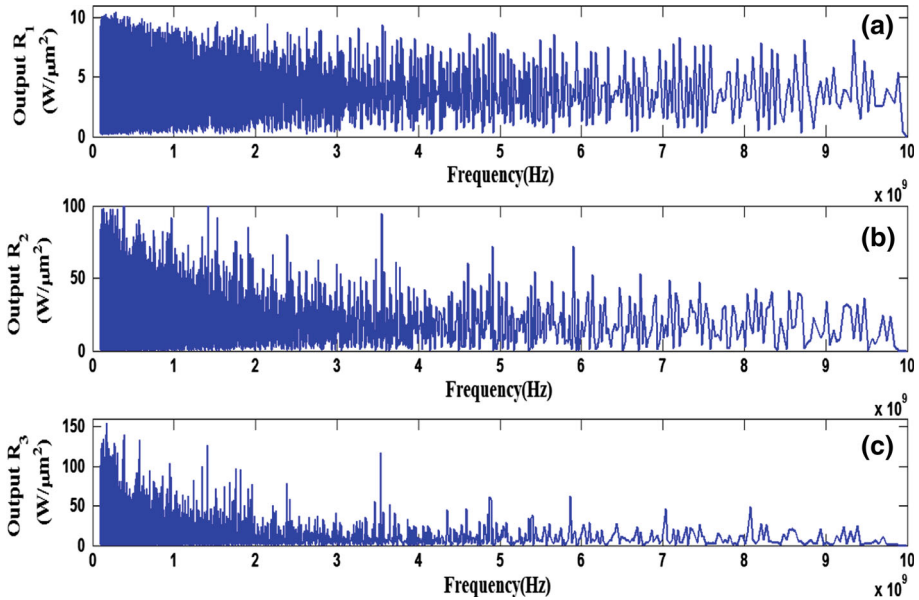
Fig. 2 Results of GHz frequency band generation **a** Output frequency from R_1, **b** Output frequency from R_2 and **c** Output frequency from R_3

resonator loss and the fractional coupler intensity loss are $\alpha = 0.5\,\text{dBmm}^{-1}$ and $\gamma = 0.1$, respectively (Amiri et al. 2013b).

3 Result and discussion

The input bright soliton pulses has power of 2W. The suitable ring radii and coupling coefficient are $R_1 = 10\,\mu\text{m}$, $R_2 = 5\,\mu\text{m}$, $R_3 = 2\,\mu\text{m}$, $\kappa_1 = 0.1$, $\kappa_2 = 0.15$, $\kappa_3 = 0.3$ $R_{ad} = 200\,\mu\text{m}$. The used semiconductor waveguide is InGaAsP/InP, where the effective core areas range from $A_{eff} = 0.50$ to $0.10\,\mu\text{m}^2$. The nonlinear refractive index is $n_2 = 2.2 \times 10^{-17}\,\text{m}^2/\text{W}$. Figure 2 shows the intensity output soliton signals from three ring resonator which support soliton pulses in the range of 0–10 GHz.

The high capacity of the soliton pulses can be obtained when an add/drop filter system is connected to the MRRs as shown in Fig. 1. Therefore, cancellation of chaotic signals is achieved which leading to generate clear signals with specific Full Width at Half Maximum (FWHM) and Free Spectral Range (FSR), applied in optical communication networks. Figure 3 shows the output intensity from through and drop ports of the add/drop filter system with specific FWHM and FSR of 3 and 85 MHz respectively.

Soliton signals can be used in optical communication where the capacity of the output signals can be improved by generation of peaks with smaller FWHM. In operation, the computing data can be modulated and input into the system via a network wireless system such as WiMAX system. The finesse of the system can be expressed by

$$finesse = \frac{FSR}{FWHM},\tag{14}$$

where increasing of the FSR or decreasing the FWHM leads to show higher finesse. The low finesse is a benefit for an optical transmitter system in which the system experiences
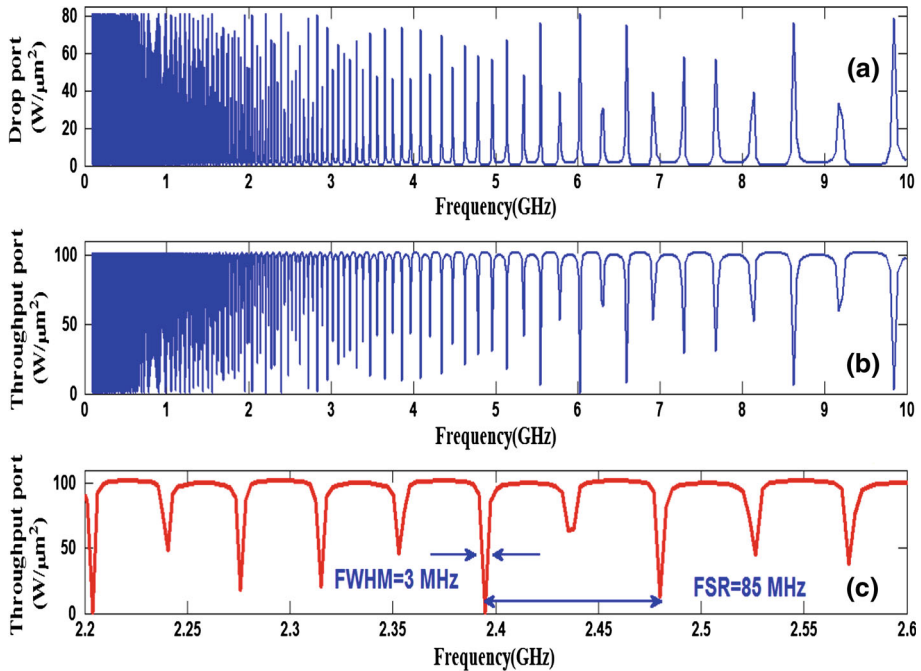
Fig. 3 Results of GHz frequency band generation **a** Drop port output signals, **b** Through port output signals and **c** Expansion of the through port output signals which shows soliton signals with FSR = 85 and FWHM = 3 MHz

uniform transmission along the transmission link. Moreover, one of the important key parameters of the ring resonator system is the finesse, where the higher finesse shows better performance (sensitivity) of this system. In this study, we use the loop of the ring resonators made of single-mode fiber optics to generate a frequency band soliton pulses, which provides and satisfies both uniform transmission and high performance (sensitivity). It means that the presented system with finesse of 28.33 shows the high performance (sensitivity), while the transmission of soliton signals is uniform. In order to transmit the multi optical soliton, the signals can be converted to the logic codes of "0" and "1" using suitable analog to digital convertor system. Figure 4 shows the generation of train of logic codes as "1101101011010101101010101111111101" respect to the threshold intensity power between 38 and 40 W/μm^2.

Therefore, soliton signals of GHz frequency band are generated, whereas the required signals can be used to perform the wireless communication network via WiMAX technology. In order to increase the capacity of microring systems, more sharp optical pulses with smaller FSR are recommended. Furthermore, the applications such as quantum repeater, quantum entangled photon source are available, which can complete the concept of quantum optical communication networks. A schematic of a WiMAX network system is shown in Fig. 5.

The fiber optic has a length of 1 km, attenuation of 0.2 dB/km, dispersion of 5 ps/nm/km, the differential group delay of 0.2 ps/km, the nonlinear refractive index of 2.6×10^{-20} m^2/W, effective area of 25 μm^2 and the nonlinear phase shift of 3 mrad. The advanced transmitter topologies are desirable for application in WiMAX communication inasmuch as they are able to provide power-efficient amplification of signals with large peak-to average power ratios (PAPRs) without compromising system linearity. The optical wireless transmitter has
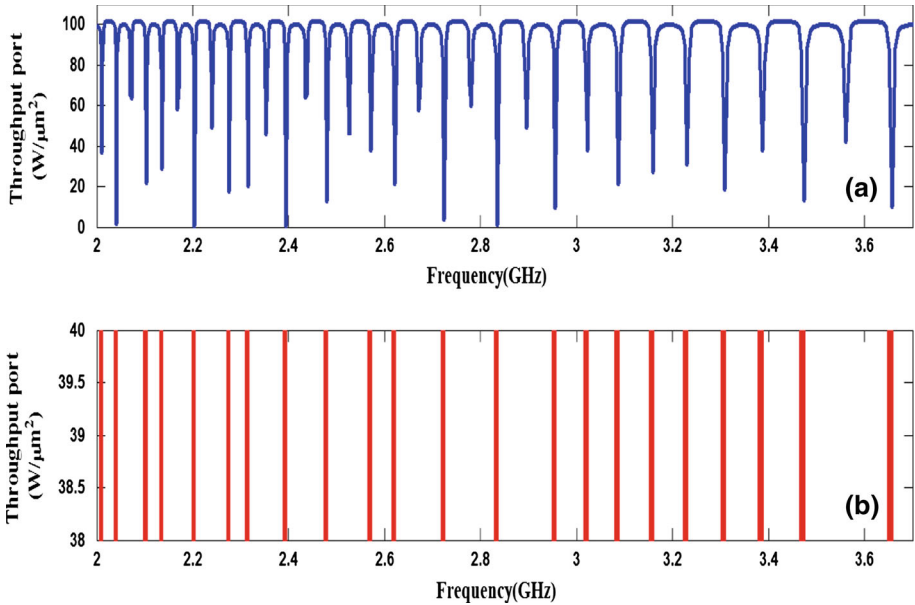
Fig. 4 Optical soliton pulses and logic codes within the range of 2 and 3.7 GHz, where **a** Throughput intensity output multi soliton pulses, **b** Generated logic codes of "11011010110101011010101111111101"
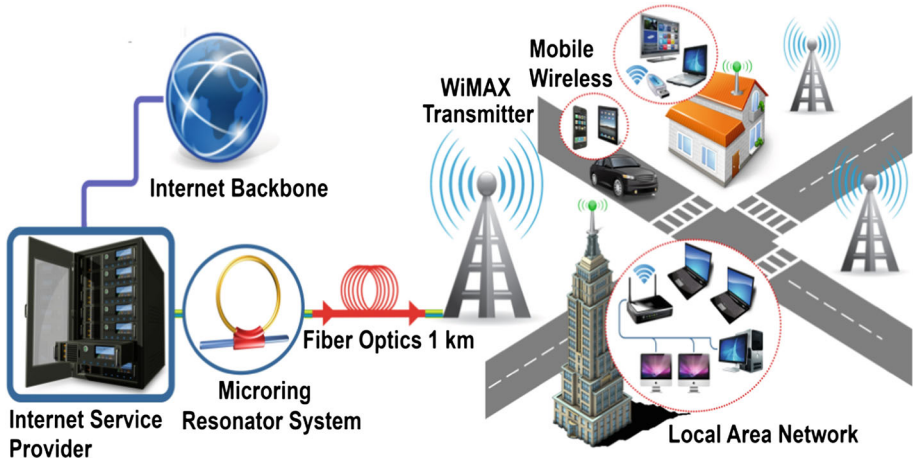

Fig. 5 WiMAX network system

an extinction ration of 10 dB, line width of 10 THz, modulation type of nonreturn-to-zero (NRZ) and rise time of $1/(\text{Bit rate}) \times 0.05$, where the optical receiver has responsivity of 1 A/W, dark current of 10 nA, a cutoff frequency of 0.75*Bit rate Hz and a thermal noise of 10^{-22} W/Hz. The transmitting of soliton logic codes using the wired and wireless transmission link is shown by Fig. 6, where the covering ranges are 1 km and 100 m respectively.

Therefore, microring resonators are suitable to generate signals with high frequency, while the logic codes (digital codes) electronically can be performed by the signals. The soliton signals can be generated and transmitted via either wire or wireless links to the required
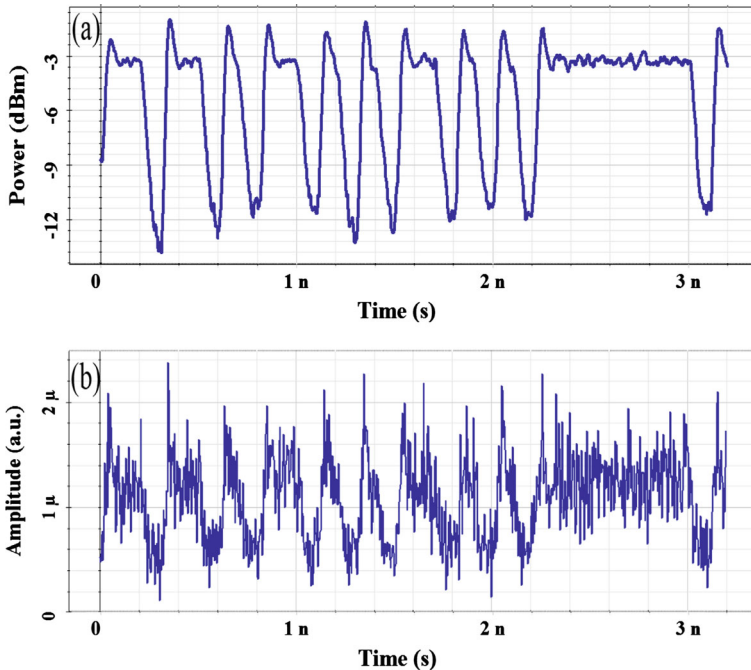
Fig. 6 Transmission of logic multi soliton pulses, where **a** Transmitted signals within a fiber optic with a length of 1 km, **b** Transmitted signals using an optical wireless transmitter with a range of 100 m

receivers. In this study the multi soliton pulses with frequency range within 2–3.7 GHz were generated and used as transmitting logic codes in wireless communication such as WiMAX, where the transmitted signal power could be detected by a suitable optical detector at the end of the transmission link with the length of 100 m. Soliton signals, as multiple carriers, can be modulated with the information, using a suitable technique, to transmit the data via a wired/wireless network system (Deepak and Chaudhary 2012). Transmission of data using optical soliton pulses in wireless communication has been investigated by several researchers (Ganapathy et al. 2011; Shahidinejad et al. 2013; Bunruangses et al. 2010; Chaiyasoonthorn et al. 2010; Pornsuwancharoen et al. 2013; Pipatsart et al. 2012; Eakkapan et al. 2012; Thammawongsa et al. 2012).

4 Conclusion

A novel system of microring resonator for GHz frequency band optical soliton generation has been demonstrated. The optical soliton is propagating via MRRs, where it can be transmitted by a wireless network system such as WiMAX system over short and long distance communication. The signal processing can be implemented by connecting nonlinear ring resonator system to a wireless network, thus providing high capacity of transmission using multi optical soliton pulses. Here, the multi soliton pulses can be generated within the nonlinear fiber optic ring resonator system. The generated soliton pulses can be converted to logic codes in order to be transmitted along a wireless network as WiMAX. Therefore signals can be transmitted and detected by the users at the end of the transmission link.

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