Optical Fiber Technology 20 (2014) 336–340

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

A secure WDM ring access network employing silicon micro-ring based remote node

Jiun-Yu Sung [a], Chi-Wai Chow [b], Chien-Hung Yeh [b,c,*], Ke Xu [d], Chin-Wei Hsu [a], Hong-Quan Su [a], Hon-Ki Tsang [d]

[a] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[b] Information and Communications Research Laboratories, Industrial Technology Research Institute (ITRI), Chutung, Hsinchu 31040, Taiwan
[c] Graduate Institute of Applied Science and Engineering, Fu Jen Catholic University, New Taipei 24205, Taiwan
[d] Department of Electronic Engineering, The Chinese University of Hong Kong, Hong Kong

ARTICLE INFO

Article history:
Received 3 January 2014
Revised 28 February 2014
Available online 18 April 2014

Keywords:
WDM access
Silicon micro-ring resonator
Wavelength hopping

ABSTRACT

A secure and scalable wavelength-division-multiplexing (WDM) ring-based access network is proposed and demonstrated using proof-of-concept experiments. In the remote node (RN), wavelength hopping for specific optical networking unit (ONU) is deployed by using silicon micro-ring resonators (SMR). Using silicon-based devices could be cost-effective for the cost-sensitive access network. Hence the optical physical layer security is introduced. The issues of denial of service (DOS) attacks, eavesdropping and masquerading can be made more difficult in the proposed WDM ring-based access network. Besides, the SMRs with different dropped wavelengths can be cascaded, such that the signals pass through the preceding SMRs can be dropped by a succeeding SMR. This can increase the scalability of the RN for supporting more ONUs for future upgrade. Here, error-free 10 Gb/s downlink and 1.25 Gb/s uplink transmission are demonstrated to show the feasibility of the proposed network.

1. Introduction

Fiber-to-the-home (FTTH) based on passive optical network (PON) can provide high bandwidth to end users cost-effectively; hence it is widely deployed in present access networks. Today's PON is time-division multiplexing (TDM) based, and the broadcasting nature of these PONs introduces security concerns to the end users and network operators [1]. Nowadays, these security concerns are mainly addressed using encryption techniques on or above the Media Access Control (MAC) layer [2,3]. Providing a more effective security in the optical physical layer other than using encryption algorithms is highly desirable since it can increase the network performance as well as providing additional dimension of network security. Ref. [4] proposed a wavelength hopping PON (WP-PON) to enhance the PON security. However, only simulation results are provided and TDM-based PON can be used.

Ref. [5] has pointed out three main security issues in the TDM-PON, including the denial of service (DOS) attacks, eavesdropping and masquerading of an optical networking unit (ONU). The DOS attack can simply be a malfunctioning or purposely corrupted uplink laser in the ONU continuously transmitting the uplink signal, which is high enough to block all the ONUs in the same TDM-PON. Eavesdropping happens when a Malicious ONU can listen to the uplink data sending from another ONU. Ref. [5] has demonstrated that reflected signals due to un-terminated or dirty connectors and fiber couplers can be high enough for a Malicious ONU to read the uplink signal sending from a Victim ONU; hence making the issue unnoticeable to network operator. Finally, masquerading is a Malicious ONU pretends to be the Victim ONU.

In this work, a secure and scalable wavelength division multiplexed (WDM) ring-based access network is proposed and demonstrated using proof-of-concept experiments. Ring-based access network has attracted significantly attenuation, and it is regarded as one of the promising architectures for the next generation access networks owing to its network protection purpose and high flexibility in wavelength management and assignment [6–9]. Here, in the remote node (RN), wavelength hopping for specific ONU is deployed by using silicon micro-ring resonators (SMR); hence the optical physical layer security is introduced. Incorporating silicon photonic devices in access networks could reduce the cost and power consumption [10], and it is being actively investigated in all over the world, such as in the EU projects: FDMA Access by

* Corresponding author at: Information and Communications Research Laboratories Industrial Technology Research Institute (ITRI) Chutung, Hsinchu 30010, Taiwan.
E-mail address: depew@itri.org.tw (C.-H. Yeh).

http://dx.doi.org/10.1016/j.yofte.2014.03.009
1068-5200/

Using Low-cost Optical Network Units in Silicon Photonics (FABULOUS); and Photonics Electronics Functional Integration on CMOS (HELIOS) [11]. The issues of DOS attacks, eavesdropping and masquerading can be made more difficult in the proposed WDM ring-based access network. Up to our knowledge, it is the first time a secure WDM access network using silicon micro-ring based remote node for wavelength hopping was proposed. Error-free (bit-error-rate (BER) < 10^{-9}) 10 Gb/s downlink and 1.25 Gb/s uplink transmission were demonstrated to show the feasibility of the proposed network.

2. Architecture and principle

Fig. 1 shows the architecture of the proposed WDM ring based system. WDM signals are transmitted from the central office (CO) to different remote nodes (RNs). Each RN as shown in inset of Fig. 1, is composed of two SMRs with separated electrode controls acting as the wavelength selector, a trigger photodiode (PD) for detecting the control information sending from the CO and an electrical signal generator. In the SMR, wavelength matches to the SMR resonant wavelength will go to the dropped port of the SMR, while other wavelengths will directly transmit to the through port of the SMR. The signal generator receives the information from the trigger PD (sent from the CO), and then generates specific electrical pattern to control the wavelength of the SMRs. Each SMR is modulated by a specific random pattern, so that the dropped wavelength of the SMR is changed randomly. Each random signal for a specific SMR is uniquely known only by the CO and the specific RN. The wavelengths sent from the CO to this particular RN are changed accordingly following this pattern, so that which wavelength is used is difficult to detect by the third party. Typically, the modulation speed for wavelength dropping by a SMR can be as high as kHz by using thermal tuning [12] and even GHz by using carrier injection [13]. This makes it difficult for an intruder to attack a specific end-user according to the known communication wavelength.

An ONU, including a downlink PD and an uplink modulator, is connected to the SMR based RN as shown in the inset of Fig. 1. For the downlink transmission, the desirable wavelength dropped by the SMR is directly received by a PD. For the uplink transmission, the transmitted optical carrier is distributed from CO. The distributed optical carrier is dropped by another SMR, modulated at the end-user's side to produce the uplink signal by using a reflective semiconductor optical amplifier (RSOA), and then is fed back to the add port of the SMR to return to the CO. Using silicon-based devices could be cost-effective for the cost-sensitive access network. Monolithic integration of SMRs and silicon PD could further reduce the cost [10,14]. The SMRs with different dropped wavelengths can be cascaded in this proposed RN. This can increase the scalability of the RN for supporting more ONUs for future upgrade.

In our proposed system, the wavelengths of each silicon ring are changed dynamically. This makes it difficult to monitor the link impairment of each RN. To achieve link impairment monitoring, data transmission stops at some pre-scheduled time slots, called "Link Monitor Window". At the "Link Monitor Window", the chosen SMR will change its monitor wavelengths rapidly and reports its existence. Some DOS attack may be achieved in typical WDM system if the monitoring wavelength of the RN is known. An intruder may report the RN alive while it is out-of-service in reality. In our proposed system, the monitoring wavelengths of each silicon ring are changed dynamically. Hence, it is much more difficult for the intruders to masquerade the RN. Fig. 2 shows the time trace of the change in wavelength of each SMR. It is also worth to mention that in this scheme, equal fixed duration of time-slot is allocated for each user as shown in Fig. 2, variable time-slot based on customer needs can be implemented.

3. Experiment

The SMR used in our experiment was fabricated by Inter-university Microelectronic Centre (IMEC). The SMR was fabricated on a silicon-on-insulator (SOI) wafer, with thicknesses of the top silicon and buried oxide (BOX) of 220 nm and 2 μm respectively. Eq. (1) describes the power transmission characteristics of a micro-ring filter [15]:

$$T_r = \frac{T_0}{1 + \left(\frac{2}{\pi}F^2\right)\sin^2\left(\frac{\beta_r l_r}{2}\right)} \qquad (1)$$

where T_0 is the transmission satisfying resonance condition, $\beta_r l_r = N \times 2\pi$, N is an integer, β_r is the propagation constant in the micro-ring, l_r is the circumference of the SMR, and the free-spectral range (FSR) = $\lambda^2/n_r l_r$, n_r is the effective index of the micro-ring waveguide, and F is the finesse. For example, Let two wavelengths λ_1 and λ_2 are coupled into the SMR filter from the input port. If λ_1 satisfies the SMR filter resonance condition, it will couple into the ring waveguide through evanescently side coupling. Then, it will appear at the drop port (signal pass). For other wavelengths not satisfying the resonance condition, such as λ_2, it will transmit to the through port (signal remove). Fig. 3 shows the measured transmission characteristics of the SMR dropped port and through port in our experiment. The 3-dB linewidth of the SMR was about 0.2 nm.

We first discuss the downlink experiment with wavelength hopping. Fig. 4 shows the proof-of-concept experimental setup for WDM downlink transmission with wavelength hopping. Two optical signals generated by distributed feedback lasers (DFBs) with wavelengths of 1559.013 nm and 1559.813 nm were combined by an optical coupler (OC) and fed into a Mach-Zehnder

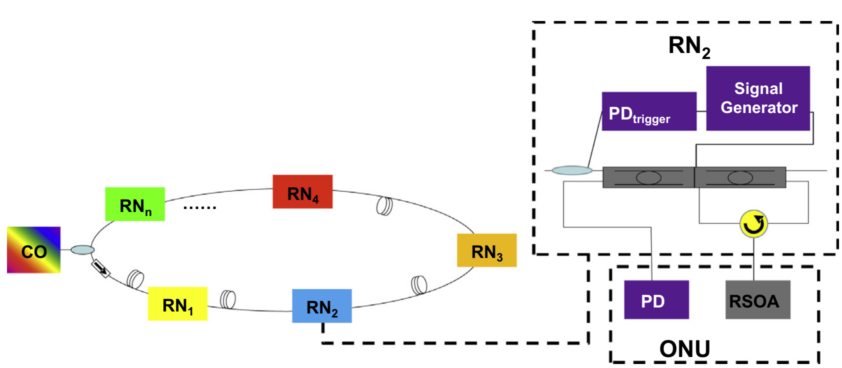

Fig. 1. Proposed architecture of the secure WDM ring based system.

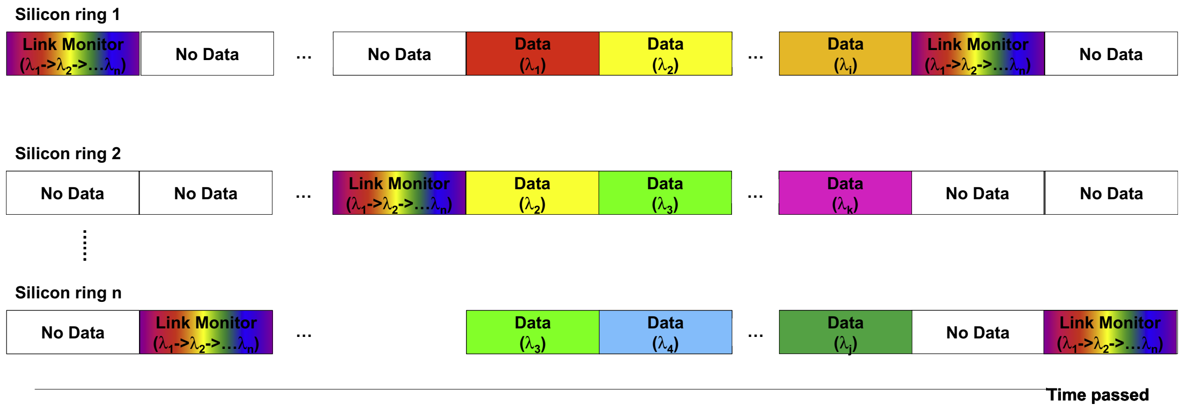

Fig. 2. Time-traces of different SMRs showing the mechanism of wavelength hopping.

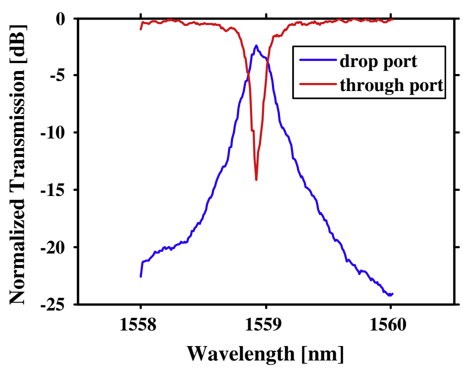

Fig. 3. Transmission characteristics for dropped and through port of the SMR used in experiment.

modulator (MZM) in the CO to produce two 10 Gb/s on-off keying (OOK) downlink signals. The two signals were launched into a 25 km standard single mode fiber (SSMF). Then the WDM signals were launched into RN_1. Inside RN_1, an electrical signal generator can be used to apply voltage pattern to the SMR to drop the 1559.013 nm signal, which was then outputted at the dropped port of the SMR and received. The 1559.813 nm signal transmitted through the RN_1 and was outputted at the through port of the SMR. The 1559.813 nm through-port signal propagated another 8 km SSMF before being received at RN_2. The insets (a)–(d) of Fig. 4 show the experimental optical spectra at different locations of the setup, showing the SMR can successfully drop one WDM wavelength channel and the other WDM channel pass to the through port. The insets (e)–(f) of Fig. 4 show two unique driving patterns that can be applied to the SMRs in RN_1 and RN_2 respectively. For example, at a specific time-slot, the first wavelength

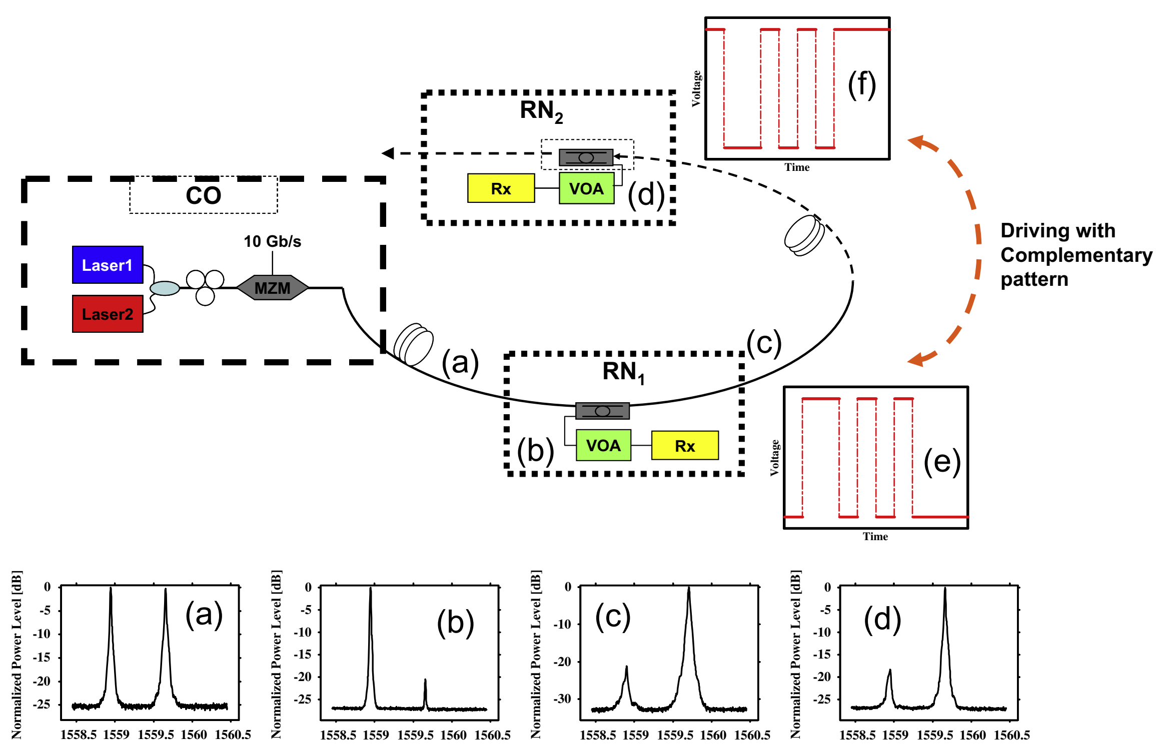

Fig. 4. Proof-of-concept experimental setup of the downlink transmission with wavelength hopping. Inset (a)–(d): measured optical spectra at different locations of the network. Inset (e)–(f): time traces of applied voltage.

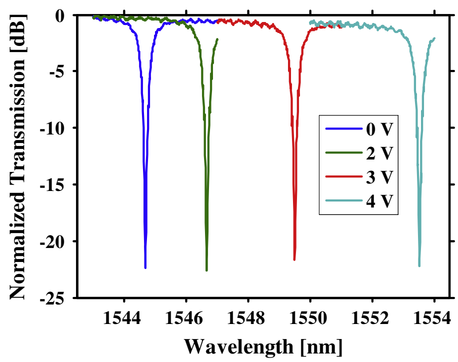

Fig. 5. Measured wavelength tuning characteristic of the SMR, showing 8.9 nm wavelength-tunability with 4 V applied voltage.

was received by RN_1 while the second wavelength was received by RN_2. For the condition of more RNs, the wavelength sharing mechanism was similar. The resonant wavelength tuning of the SMR can be achieved by thermal tuning, and the measured wavelength tuning characteristic is shown in Fig. 5. We can observe that 8.9 nm wavelength-tunability can be achieved with 4 V. For 0.8 nm ITU channel spacing, this 8.9 nm wavelength spacing can support more than 11 wavelengths for wavelength hopping of a specific RN. Precise wavelength management involves higher level protocol; hence it was not demonstrated in this experiment.

Fig. 6 shows the proof-of-concept experimental setup for uplink transmission. A 1559.013 µnm wavelength continuous-wave (CW) carrier was distributed from CO to the RN_1 30 km away. At the dropped port of the SMR, the CW carrier was launched into a RSOA through an optical circulator. The RSOA has a direct modulation bandwidth of 1 GHz, and it was driven by 1.25 Gb/s OOK signal. The modulated uplink signal was reflected back. Here, an optical bandpass filter was used to emulate the effect of the uplink signal passing back to the SMR. After the optical bandpass filter, the uplink signal was received.

Fig. 7(a) shows the measured downlink signal bit error rate (BER) performance. Error-free (BER < 10^{-9}) transmissions were achieved in all cases. About 2 dB power penalties were observed between the 25 km transmission (detected at SMR drop port) and 25 km + 8 km (detected at SMR through port). This may result from the extinction ratio (ER) difference between the dropped port and the through port, and also the dispersion by the additional 8 km SMF. The corresponding 10 Gb/s eye-diagrams of captured at the drop and through ports are included in Fig. 7. Fig. 7(b) showed the measured uplink signal BER performance. Different ROSA bias conditions were compared. It was observed that the BER < 10^{-9} was achieved for bias currents higher than 40 mA. The worse BER performance below 50 mA may result from insufficient injection power. While the bias current higher than 60 mA, the BER performance degraded gradually. This may result from saturation induced low signal ER.

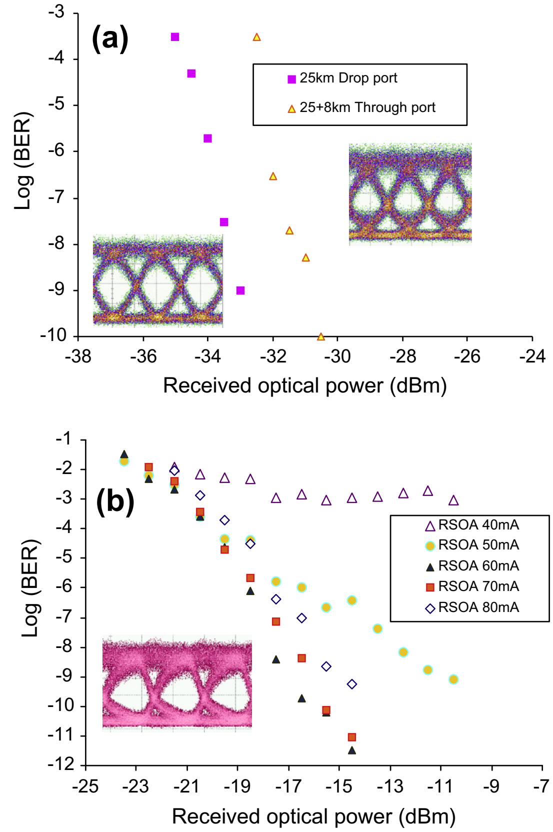

Fig. 7. Measured BER performance for the (a) downlink transmission and (b) uplink transmission.

4. Conclusion

In this work, a secure and scalable WDM ring-based access network was proposed and demonstrated using proof-of-concept experiments. The optical physical layer security was introduced to the network. The issues of DOS, eavesdropping and masquerading can be prevented in the proposed network. The characteristics of the SMR providing wavelength hopping to offer the optical physical layer security were discussed. Besides, the SMRs with different dropped wavelengths can be cascaded, such that the signals pass through the preceding SMRs can be dropped by a succeeding SMR. This can increase the scalability of the RN for supporting more ONUs for future upgrade. Moreover, the use of silicon-photonic devices provides the possibility for low cost system integration. Error-free 10 Gb/s downlink transmissions were measured at the dropped and pass-through signals of the SMR respectively. RSOA was used to modulate the SMR dropped CW carrier signal to generate the uplink OOK signal. An Error-free 1.25 Gb/s uplink transmission were achieved. Because the SMR is used as an

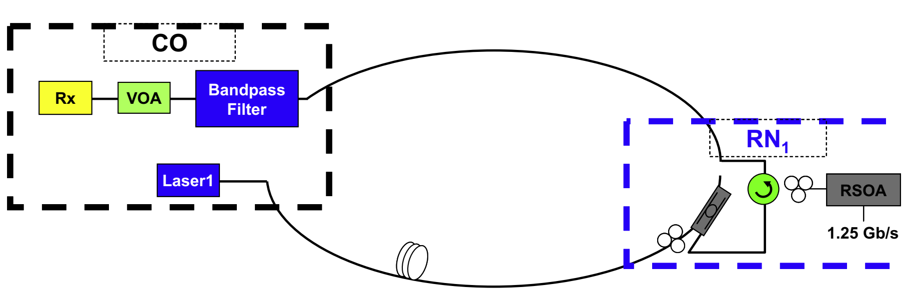

Fig. 6. Proof-of-concept experimental setup of the uplink transmission.

add-drop filter for implementing wavelength hopping, the transmission data rate is not determined by the SMR. The bit rate of the uplink signal was limited by the direct modulation bandwidth of the RSOA. Higher data rate can be achieved if electro-absorption modulator (EAM) is used.

Acknowledgment

This work was supported by the National Science Council, Taiwan, ROC, under Contract NSC-101-2628-E-009-007-MY3, NSC-100-2221-E-009-088-MY3 and the Hong Kong University Grants Council Special Equipment Grant SEG-CUHK01.

References

[1] C.-H. Yeh, C.-W. Chow, C.-H. Wang, F.-Y. Shih, Y.-F. Wu, S. Chi, Using four wavelength-multiplexed self-seeding Fabry–Perot lasers for 10 Gbps upstream traffic in TDM-PON, Opt. Exp. 16 (2008) 18857–18862.
[2] S. Roh, S. Kim, Security model and authentication protocol in EPON-based optical access network, in: Proc. 5th Annu. Conf. on Transparent Optical Networks, 2003, vol. 1, pp. 99–102.
[3] K. Kim, K. Han, T. Yoo, The implementation of the link security module in an EPON access network, in: Proc. Asia–Pacific Conf. on Commun., 2005, pp. 1–5.
[4] A. Harris, D.R. Jones, K.H. Horbatuck, A. Sierra, A novel wavelength hopping passive optical network (WH-PON) for provision of enhanced physical security, J. Opt. Commun. Netw. 4 (2012) 289–295.
[5] D. Gutierrez, J. Cho, L.G. Kazovsky, TDM-PON security issues: upstream encryption is needed, in: Proc. of OFC, 2007, paper JWA83.
[6] J. Prat, J.A. Lazaro, K. Kanonakis, I. Tomokos, New FTTH architectures for NG-PON-2, in: OSA Tech. Dig. Access Networks and In-House Communications, Karlsruhe, Germany, Paper ATuA4.
[7] H.H. Lu, S.J. Tzeng, Y.L. Liu, "Intermodulation distortion suppression in a full-duplex radio-on-fiber ring network, IEEE Photon. Technol. Lett. 26 (2004) 602–604.
[8] C.H. Yeh, C.W. Chow, S.P. Huang, J.Y. Sung, Y.L. Liu, C.L. Pan, Ring-based WDM access network providing both Rayleigh backscattering noise mitigation and fiber-fault protection, J. Lightw. Technol. 30 (Oct) (2012) 3211–3218.
[9] C.W. Chow, C.H. Yeh, Y.F. Wu, Y.H. Lin, F.Y. Shih, S. Chi, Rayleigh backscattering circumvention in ring-based access network using RSOA-ONU, IEEE Photon. Technol. Lett. 23 (16) (Aug. 2011) 1121–1123.
[10] K. Xu, L.G. Yang, J.Y. Sung, Y.M. Chen, Z.Z. Cheng, C.W. Chow, C.H. Yeh, H.K. Tsang, Compatibility of silicon Mach–Zehnder modulators for advanced modulation formats, J. Lightw. Technol. 31 (15) (2013) 2550–2554.
[11] B. Charbonnier, S. Menezo, P. O'Brien, A. Lebreton, J.M. Fedeli, B. Ben Bakir, Silicon photonics for next generation FDM/FDMA PON, J. Opt. Comm. Netw. 4 (2012) A29–A37.
[12] X. Wang, J.A. Martinez, M.S. Nawrocka, R.R. Panepucci, Compact thermally tunable silicon wavelength switch: modeling and characterization, IEEE Photon. Technol. Lett. 20 (2008) 936–938.
[13] C.W. Chow, C.H. Yeh, S.M.G. Lo, C. Li, H.K. Tsang, Long-reach radio-over-fiber signal distribution using single-sideband signal generated by a silicon-modulator, Opt. Exp. 19 (2011) 11312–11317.
[14] K. Xu, Z. Cheng, C.Y. Wong, H.K. Tsang, Tunable integrated variable bit-rate DPSK silicon receiver, Opt. Lett. 37 (2012) 4738–4740.
[15] B. Liu, A. Shakouri, J.E. Bowers, Passive microring-resonator-coupled lasers, Appl. Phys. Lett. 79 (2001) 3561–3563.