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Abstract. Integrated waveguide microwave photonic filters (MPFs) have the potential to bring down volume, weight, and power consumption of signal processing equipment besides the common advantages of discrete-component-based MPFs. A polysiloxane-liquid polymer-based optical waveguide microring resonator was designed and fabricated by a simple ultraviolet-based soft-imprint technology, with which the quasi-single-sideband filtering for the 10 to 22 GHz microwave signal was realized and 20 Mbps quadrature phase shift keying signal carried by 14.35 GHz microwave transmission over a 25 km single mode fiber was demonstrated. [DOI: 10.1117/1.3657818]

Subject terms: polymer waveguide; microring resonator; microwave photonic filter; radio over fiber.

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1 Introduction

Various microwave photonic filters (MPFs) have been extensively studied in view of their promising applications to broadband wireless access networks, radio over fiber systems, radars for moving target identification, satellite communication systems, and so forth.[1] These filters leverage the advantages of photonic signal processing by moving the filtering operation to the optical domain, which offers the benefits of wide bandwidth, low loss, and natural immunity to electromagnetic interference.[2,3]

Generally speaking, the majority of MPFs have been implemented with commercially available discrete components such as single mode fibers (SMFs), couplers, fiber Bragg gratings, and one or more optical sources.[1,2] In contrast to discrete components, integrated waveguide MPFs have the potential to bring down volume, weight, and power consumption of signal processing equipments,[4] which is essentially important in aircraft and space satellite communication systems,[5–7] especially if integration with electro-optical modulators (EOMs) and photodetectors (PDs) is possible.

Polymer is a promising material of choice for photonic integrated waveguide devices because, when synthesized and processed properly, it offers high performance in terms of low-loss, smaller birefringence, high tunability in terms of large thermo-optic coefficient, environmentally stable, high yields, and low cost.[8] Moreover, it provides an ideal integration platform where foreign material systems such as yttrium

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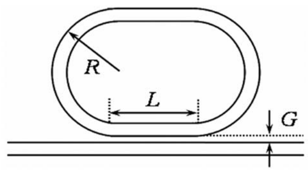
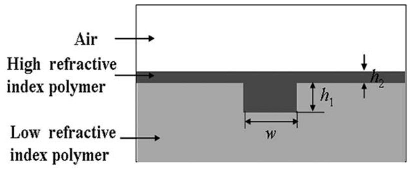


(a)



(b)

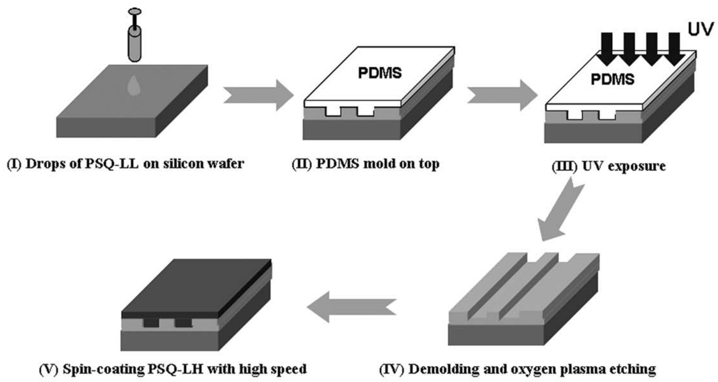
Fig. 1 (a) Schematic of microring resonator and (b) cross section of polymer waveguide.

iron garnet, lithium niobate, and semiconductor devices (such as lasers, detectors, and amplifiers) can be inserted into an etched groove in a planar lightwave circuit to enable full function modules on a single substrate.[9,10] Polymer-based integrated waveguide devices for microwave photonic signal processing, such as the compact optical true time delay lines,[11,12] high bandwidth EOMs,[13] and reconfigurable bandpass filters,[14] have been demonstrated.

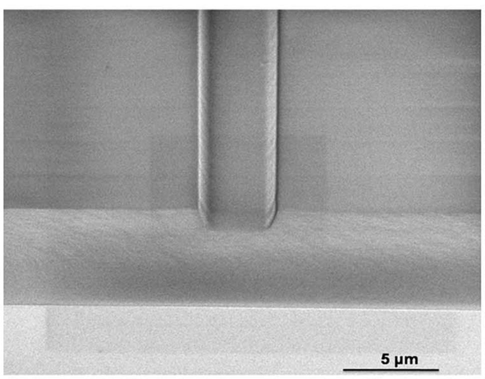
In this paper, a polysiloxane-liquid (PSQ-L) polymer-based microring resonator was designed and fabricated by a simple ultraviolet (UV)-based soft-imprint technology, with which the quasi-single-sideband (SSB) filtering response was realized. The chromatic dispersion induced fading effect was suppressed effectively and a 20 Mbps quadrature phase shift keying (QPSK) signal carried by 14.35 GHz microwave was transmitted successfully over 25 km SMF.

2 Polymer-Based Waveguide Microring Resonator

With the polymeric material PSQ-L developed in our group,[15,16] an all-pass type single microring resonator [Fig. 1(a)] with an inverted ridge waveguide cross section [Fig. 1(b)] as a notch filter was designed and fabricated by a UV-based soft-imprint technology.



(a)



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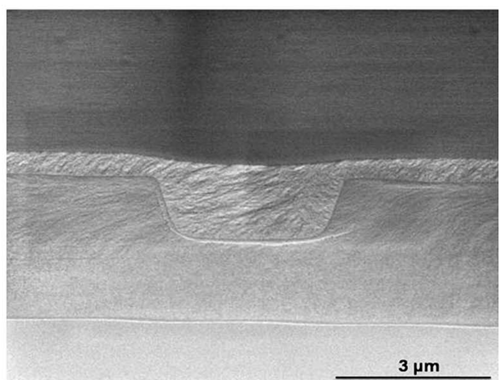
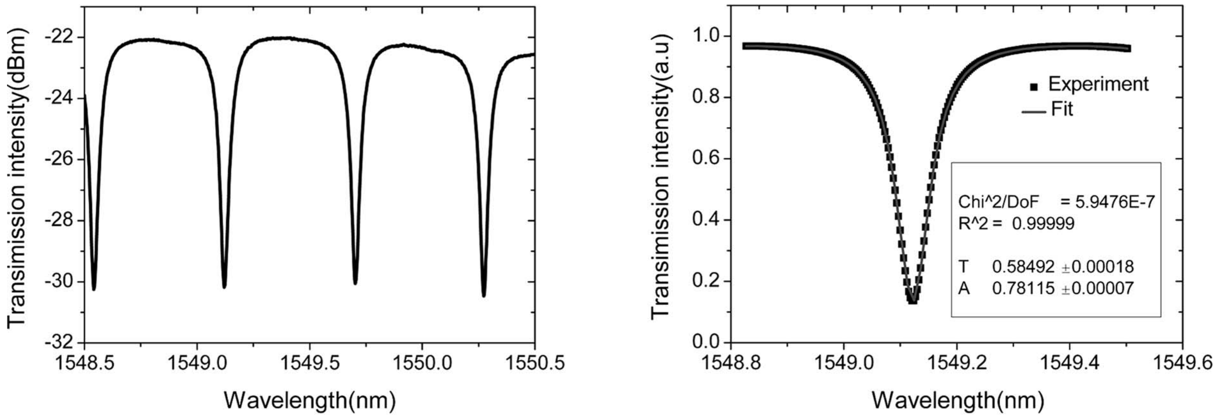


(c)

Fig. 2 (a) UV-based soft-imprint flow, (b) SEM picture of imprinted under-cladding trench, and (c) waveguide cross section after spin-coating the high refractive index layer.



(a) (b)

Fig. 3 (a) The measured optical transmission spectrum of the polymer-based microring resonator (TE mode) and (b) the parameters of the microring resonator through fitting the experimental data.

The normalized transmission function of the microring resonator can be expressed as[17]

$$I(\lambda) = \frac{T - 2\sqrt{T}\sqrt{A}\cos\left[\frac{2\pi}{\lambda}\cdot n_{eff}(2\pi R + 2L)\right] + A}{1 - 2\sqrt{T}\sqrt{A}\cos\left[\frac{2\pi}{\lambda}\cdot n_{eff}(2\pi R + 2L)\right] + TA}, \tag{1}$$

where R is the radius of the ring; L is the straight waveguide length of the directional coupler; A is the power attenuation coefficient per round-trip; T is the power transmission coefficient of the directional coupler; n_{eff} is the effective index of the waveguide; λ is the wavelength of optical wave in vacuum. The ring is on resonance when $n_{\mathrm{eff}}(2\pi R + 2L) = m\lambda_m$, where m is an integer. Equation (1) shows that the resonant wavelength λ_m is eliminated from the output of the microring and the maximal extinction ratio (ER) occurs when the critical coupling condition ($T = A$) is satisfied.[17] With the refractive indexes of core (PSQ-LH, $n_1 = 1.52$) and cladding (PSQ-LL, $n_2 = 1.45$) waveguides, the designed structural parameters of the microring resonator (shown in Fig. 1) are as follows: $R = 400\ \mu$m, $L = 150\ \mu$m, $G = 1\ \mu$m, $w = 3\ \mu$m, $h_1 = 2\ \mu$m and $h_2 = 0.8\ \mu$m, which fulfill the single-mode waveguide condition and negligible bending loss.

The simple UV-based soft-imprint technology as shown in Fig. 2(a) is used for the fabrication of the waveguide microring resonator. Unlike in conventional imprint processes, the imprint step for structuring is done first on the cladding layer rather than on the core layer and is followed by a spin-coating step to fill the imprinted trench with core layer material. This waveguide cross section design smartly avoids critically controlling the thickness of the residual core layer. Figures 2(b) and 2(c) show the imprinted under-cladding trench and waveguide cross section after spin-coating the high refractive index layer, respectively.

3 Experimental Results

3.1 *Optical Transmission Response*

The PSQ-L polymer-based microring resonator can work at optical fiber communication bands, such as 1310 and 1550 nm.[15,16] The optical transmission spectrum of the fabricated microring resonator was measured by coupling light from a tunable laser (at 1550 nm band) to the waveguide via a lensed fiber. The transmitted light was also collected by a lensed fiber to the optical power meter. A polarization controller was used at the input port to select the polarization state of light. Figure 3 shows the measured transverse electric (TE) mode optical transmission spectrum of the microring resonator. The ER of 8 dB at the output port is obtained. The free spectrum range of the ring is about 0.582 nm as expected due to the large ring radius. The full-width at half-maximum (FWHM) is about 0.077 nm. By taking the ratio between the resonant wavelength and FWHM, the Q-factor of about 2.0×10^4 is calculated. By fitting the experimental data with Eq. (1), T and A can be extracted as shown in Fig. 3(b). T is about 0.58, which means that 42% of the input optical power is coupled from the straight waveguide into the ring; A is about 0.78, which means 22% of the optical power is depleted after optical wave propagation per round-trip. Due to the optical loss of the waveguide microring resonator, the power of the resonant wavelength will be cut down, and it can be used as a notch filter.[17]

3.2 *Quasi-SSB Filtering Response*

Figure 4 shows the schematic diagram of the experiment setup for the polymer-based microring resonator used as a notch filter to realize the SSB radio over fiber transmission. An optical wave from the tunable laser source (TLS) is intensity-modulated by a radio-frequency (RF) signal generated from RF source (RFS). The output field is then applied to the polymer-based microring resonator. The erbium-doped fiber amplifier (EDFA) is used to compensate the coupling loss between the lensed fibers and the waveguides and the insertion loss of the polarization controller (PC). After transmitting over SMF, the optical property is measured by the

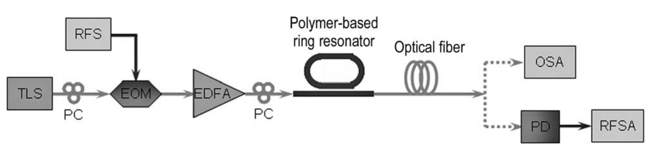


Fig. 4 Schematic diagram of the experiment setup.

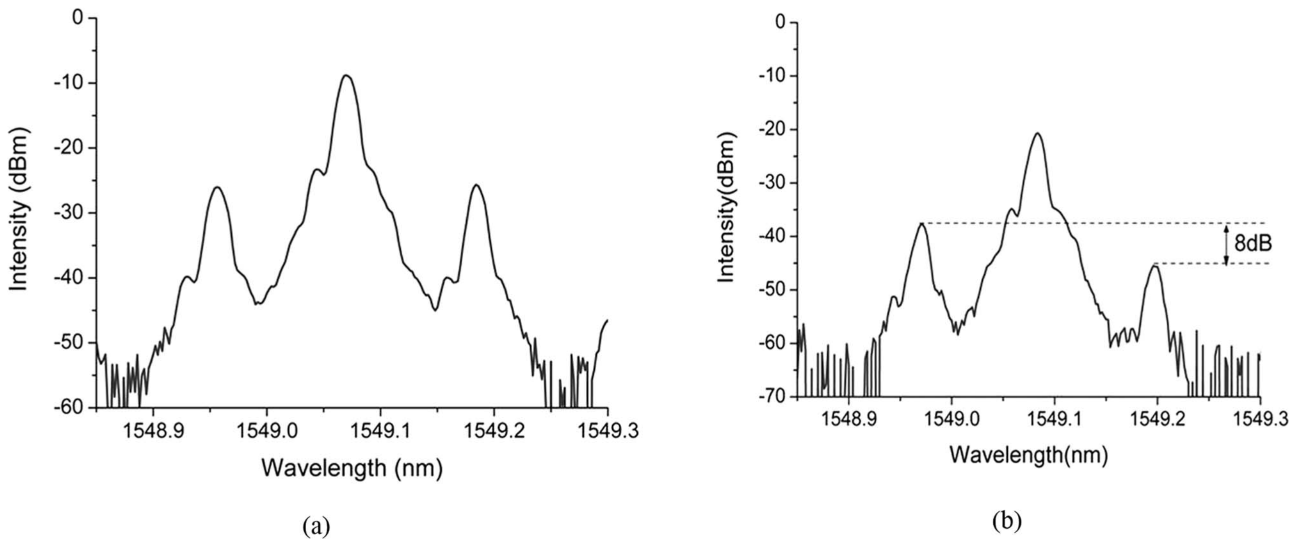


Fig. 5 Measured optical spectrums of the RF modulated optical wave (a) before and (b) after the polymer-based ring resonator.

optical spectrum analyzer (OSA) and the RF signal property from PD is measured by the RF spectrum analyzer (RFSA), respectively. Discrete EOM is used in this proof-of-principle demonstration, but it can eventually be integrated on the chip in the ultimate design. The polymer-based microring resonator serves as a notch filter to suppress one of the double sidebands (DSBs) of the microwave modulated optical wave. Then the SSB transmission over the SMF can be realized.

The sideband of the microwave modulated optical wave will be suppressed when it is located at the resonant wavelength of the polymer-based microring resonator. Figures 5(a) and 5(b) give the measured optical spectrums of the microwave (14.35 GHz) modulated optical wave before and after the microring resonator. It can be seen that the right sideband is suppressed of about 8 dB. The SSB filtering was not realized completely because the critical coupling condition[17] was not satisfied. So the name of quasi-SSB filtering should be proper for the current polymer-based microring resonator.

The SSB filtering response can also be achieved by varying the optical wave frequency from the TLS when the frequency of the input microwave signal varies. In the experiment the optical wave from the TLS was selected to the proper frequency so that the right sideband frequency of the microwave modulated optical wave was placed at the resonant frequency of the polymer-based microring resonator. Figure 6(a)–6(d) show the quasi-SSB filtering response with microwave signal frequency from 10 to 22 GHz.

The suppression magnitude of the sideband is mainly decided by the ER of the waveguide microring resonator. Its variation in a certain range for different microwave frequency in Figs. 6(a)–6(d) was caused by the instability of the polymer-based microring resonator, which is an important issue to be taken into account. The optical notch response of the microring resonator could drift in wavelength due to changes in temperature since in polymer the refractive index depends on this parameter. Changes in optical power when high power signals are used also result in wavelength drifts. Many solutions are available in order to provide stability to the system, such as the athermal waveguide design,[18] or dynamically controlling the refractive index of polymer by means of Kerr effect by applying an electrical field when the polymer has the electro-optical property.[19] Improving the ring resonator design and its fabrication process would provide better Q-factor and higher ER.

3.3 *RF Carrying QPSK Signal Over Fiber Transmission*

Due to the chromatic dispersion of the SMF, the detected RF power of the DSB signal as shown in Fig. 4(a) suffers from the fading effect.[20] The detected RF power will vary approximately as[21]

$$P_{f_{RF}} \propto \cos\left(\frac{\pi L D \lambda_C^2 f_{RF}^2}{c}\right), \tag{2}$$

where D and L are the dispersion coefficient and the length of the SMF, λ_C is the optical carrier wavelength, and f_{RF} is the microwave frequency. It attenuates as the chromatic dispersion accumulates over the long SMF and it vanishes when the product of the microwave frequency and the accumulated chromatic dispersion meets a certain value. However, the SSB signal transmission will avoid this chromatic dispersion induced fading effect, which can be realized by the fiber Bragg grating filter[22] or the dual-electrode Mach–Zehnder modulator.[21]

To demonstrate the validity of quasi-SSB filtering response of the polymer-based microring resonator, a QPSK signal of 20 Mbps carried by 14.35 GHz microwave was transmitted over 25 km SMF. For comparison, the DSB signal transmission was also tested, where the equal insertion loss of the integrated waveguide chip was provided by a tunable optical attenuator.

For the DSB signal transmission as shown in Fig. 7, the signal property deteriorated severely after the 25 km SMF with the error vector magnitude (EVM) from 4.6% to 54.4% and the signal-to-noise ratio (SNR) from 26.6 to 5.2 dB. For the quasi-SSB one as shown in Fig. 8, the signal property remained well with the EVM from 5.3% to 9.9%, the SNR from 25.5 to 20.6 dB before and after the 25 km SMF transmission, respectively. Compared with DSB signal transmission, the quasi-SSB microwave carrying QPSK signal is transmitted over 25 km SMF successfully.

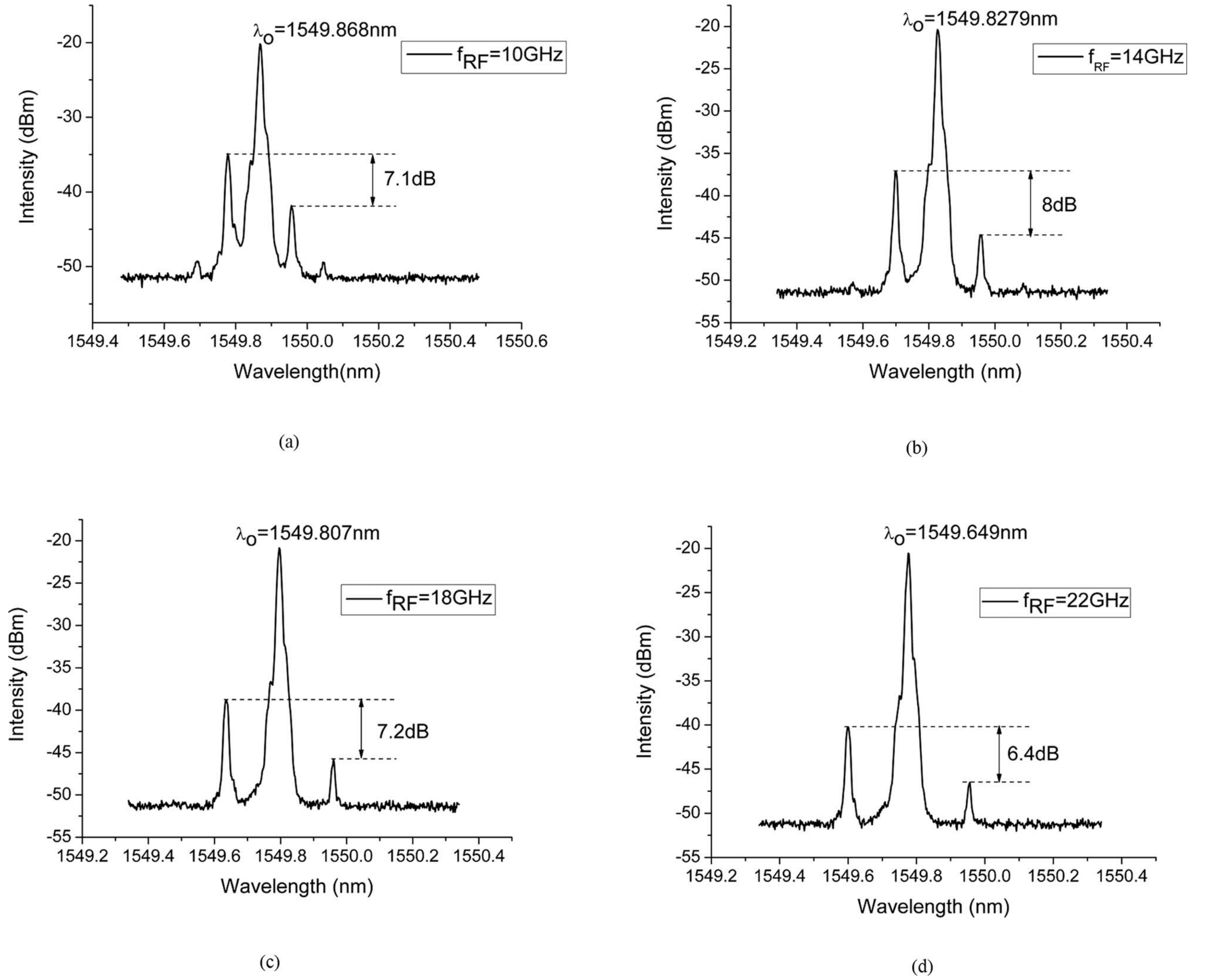


Fig. 6 Quasi-SSB filtering response of the polymer-based ring resonator with input microwave frequency of (a) 10 GHz, (b) 14 GHz, (c) 18 GHz, and (d) 22 GHz.

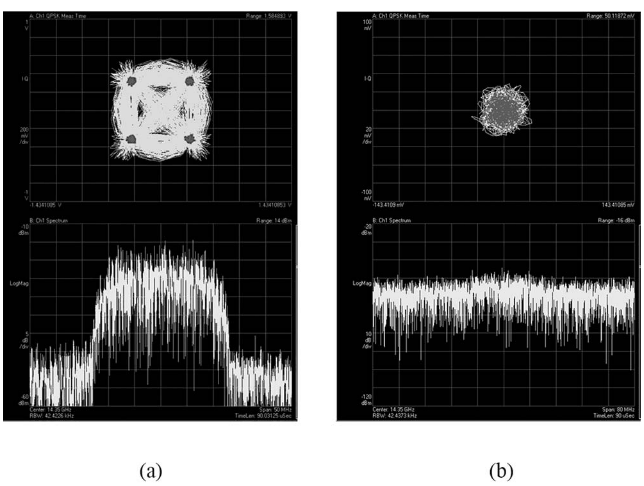


Fig. 7 DSB carrying QPSK signal transmission (a) before and (b) after 25 km SMF.

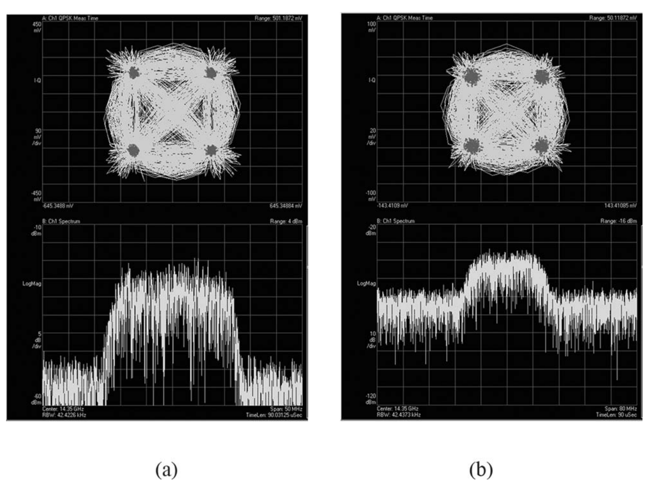


Fig. 8 Quasi-SSB carrying QPSK signal transmission before (a) and after (b) 25 km SMF.

4 Conclusion

In summary, an integrated waveguide microring resonator based on PSQ-L polymer was designed and fabricated by a simple UV-based soft-imprint technology. The quasi-SSB filtering response was achieved effectively by locating the sideband frequency of microwave modulated optical wave at the resonant frequency of the microring resonator. The chromatic dispersion caused fading effect was suppressed by the integrated waveguide filter with the demonstration of successful transmission of a 20 Mbps QPSK signal carried by 14.35 GHz microwave over 25 km SMF.

The ER of the microring resonator in the experiment was not very high since the critical coupling condition was not achieved properly. To improve the SSB filtering performance, further work of filter design and fabrication process should be carried out, such as cascading ring resonators, combination with Mach–Zehnder interferometer, and low waveguide loss.

Acknowledgments

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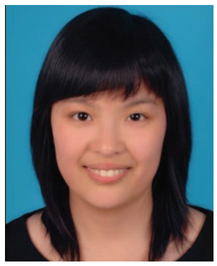

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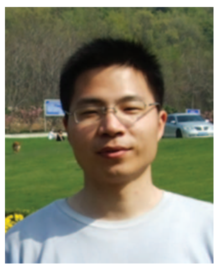

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Jinyan Wang: biography and photograph not available.

Xigao Jian: biography and photograph not available.

Geert Morthier received an MSc degree in electrical engineering and a PhD degree from Ghent University, Ghent, Belgium, in 1987 and 1991, respectively. Since 1991, he has been a member of Interuniversity Microelectronics Center, Ghent University, Ghent, Belgium, and since 2001, he is a part-time professor at Ghent University. His current research interests include the modeling and characterization of optoelectronic and photonic components, and different types of all-optical flip-flops for optical packet switching.

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