Long-reach radio-over-fiber signal distribution using single-sideband signal generated by a silicon-modulator

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Abstract: The integration of passive optical network (PON) and radio-over-fiber (ROF) networks could provide broadband services for both fixed and mobile users in a single and low-cost platform. Combining the long-reach (LR)-PON (>100 km) and the LR-ROF can further reduce the cost by simplifying the network architecture, sharing the same optical components and extending the coverage of ROF network. However, the transmission and distribution of ROF signal in LR network is very challenging due to the chromatic dispersion generated periodic power fading and code time-shifting effects in the optical fiber. In this work, we propose and experimentally demonstrate a LR-ROF signal distribution using single-sideband (SSB)-ROF signal generated by a silicon ring-modulator. The silicon modulator is compact and has low power consumption. Besides, one unique feature of the silicon ring-modulator is that it only modulates the signal wavelength at the resonant null. This makes it very suitable for the generation of the SSB-ROF signal. Numerical comparison of the SSB-ROF with the double-sideband (DSB)-ROF and optical carrier suppress (OCS)-ROF signals; as well as the fabrication of the silicon ring-modulator will be discussed.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2360) Fiber optics links and subsystems; (350, 4010) Microwaves.

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1. Introduction

Extensions and enhancements for the present passive optical network (PON) for providing higher data rate with simplified network architectures have been the subject of research recently [1–4]. Wavelength division multiplexed (WDM) long-reach PON (LR-PON) has been proposed [1–4] for combining the separate metro and access networks into a single system. This approach can reduce the number of network elements and reduce the network cost and power consumption. On the other hand, optical wireless access network using radio-over-fiber (ROF) technique is promising. The advantage of ROF lies in its centrally managed architecture, which allows the complicated electronic signal processing at many different base stations and antenna sites (and their associated operating expenses of site rental, power and maintenance) can be centralized and performed at central office (CO). The implementation of ROF allows the processed radio frequency (RF) signal to be transmitted to and from the antenna sites in the optical domain. ROF technique cannot only simplify the antenna sites by using simple and low-cost remote-antenna-units (RAUs), but also can extend the reach of the RF signal distribution by using low-loss optical fiber. It is also believed that the integration of PON and ROF networks can provide broadband services for both fixed and mobile users in a single platform. The integration of the LR-PON and the LR-ROF can further reduce the cost by sharing the same optical components and extending the ROF network to cover larger area.

Although the merging of standard-reach (~20 km) PON and ROF access network has received more attention recently [5], the research of integrating the LR-PON with the LR-ROF has attracted little attention. One possible reason is the challenge in the distribution of RF signal in LR network. When the ROF signal is propagating in an optical fiber, chromatic dispersion causes a differential delay to be progressively added to the sidebands and the carrier. For example, in the commonly used double-sideband (DSB) with carrier ROF signal, propagation of the three optical tones (optical carrier and the two sidebands) in fiber results in repetitive, length dependent power fluctuation in the received signal (called power fading effect) [6,7]. Schemes such as remote up-conversion at the remote node using optical-electrical-optical (OEO) [8] or four-wave-mixing (FWM) in a semiconductor optical amplifier (SOA) [9] can effectively extend the ROF transmission distance. However, these require electrical control and processing during the fiber transmission. Optical two tones signal, such as optical carrier suppression (OCS) signal [10] can mitigate the power fading effect; however time-shifting of the data carried by the optical two tones due to the chromatic dispersion is still severe, giving rise to unacceptable errors in the transmission. Side-sideband (SSB) ROF signal could also reduce the power fading effect, but the generation of the SSB ROF signal requires tight optical filtering [10] or separate modulation and combination of the sidebands [11,12].

In this work, we propose and demonstrate a LR ROF signal transmission and distribution using SSB-ROF signal generated by a silicon ring-modulator. The silicon modulator is compact and has low power consumption. One unique feature of the silicon ring-modulator is that it only modulates the signal wavelength located at the resonant null. This makes it very suitable for encoding data on one of the sidebands of the optical two tones signal without the need of the separation of the sidebands as in [11,12]. The paper will compare numerically the

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performance of the SSB-ROF with the DSB-ROF and OCS-ROF schemes and describe the fabrication of the silicon ring-modulator. Experimental demonstration of the LR distribution of the SSB-ROF signal shows that error free 100 km single mode fiber (SMF) transmission can be achieved.

2. Comparison of different ROF signals in LR transmissions

First we analyze different ROF signals in the LR networks. It was performed by using VPI Transmission Maker V7.5. 1-Gb/s non-return-to-zero (NRZ) baseband data modulated onto a 60 GHz carrier was used in all cases. Figure 1 shows the simulation setup of ROF signal generation using DSB, OCS and conventional SSB, with the corresponding simulated optical spectra (resolution 0.01 nm), time-domain ROF signal at back-to-back (0 km) and 100 km SMF transmission (dispersion parameter: 17 ps/nm/km), and the corresponding down-converted 1 Gb/s eye diagrams.

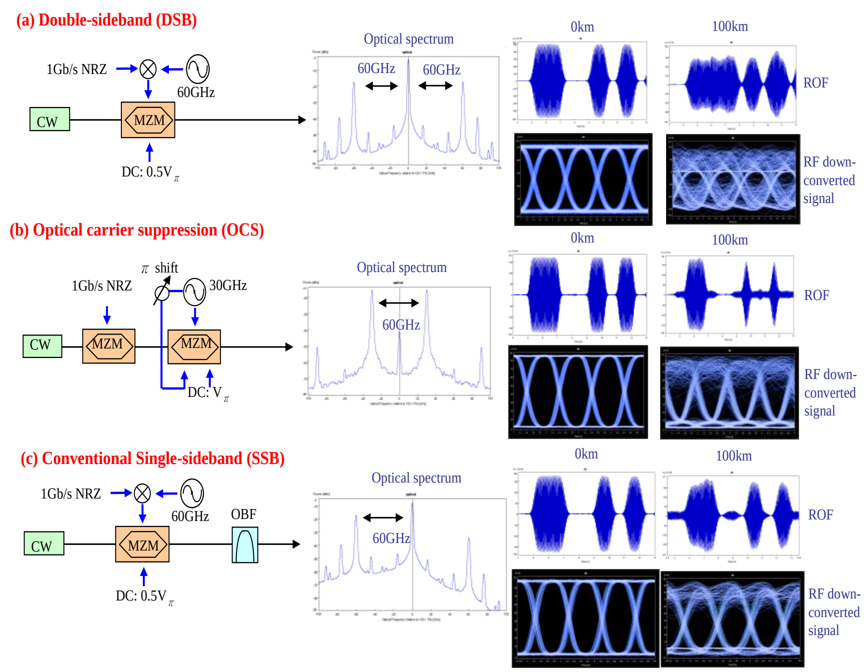

Fig. 1. Simulation setups, optical spectra, time-domain patterns and eye-diagrams at 0 km and 100 km of the (a) DSB, (b) OCS and (c) conventional SSB-ROF signals.

The DSB signal was generated via a Mach-Zehnder modulator (MZM), which was driven by an electrically mixed signal (using an RF mixer) of the baseband 1 Gb/s NRZ and the 60 GHz clock, as shown in Fig. 1(a). The OCS signal generation is shown in Fig. 1(b); the optical baseband signal was generated by the first MZM driven by a 1 Gb/s electrical NRZ signal. The second MZM was driven by a RF signal at 30 GHz. By biasing the MZM at 0.5 V_π, an OCS signal with upper and lower-sidebands separation of 60 GHz was produced. The generation of the conventional SSB-ROF signal was similar to that of the DSB signal. An offset optical bandpass filter (OBF) (1st order Gaussian shaped, 100 GHz 3-dB bandwidth, offset by 60 GHz) was used after the MZM to suppress one sideband (> 20 dB) of the optical DSB signal, hence producing the SSB signal as shown in Fig. 1(c). All the signals were detected by using a photodiode (PD) followed by a Bessel forth order bandpass filter (BPF) at center frequency of 60 GHz and bandwidth (BW) of 5 GHz. The RF down-converted signals were measured by multiplying the RF signal with a 60 GHz clock with proper phase delay. As shown in the simulated optical spectrum in Fig. 1(a), the DSB optical mm-wave consists of three dominant tones at $\omega_c - \omega_m$, ω_c, $\omega_c + \omega_m$, where the ω_c and ω_m are the frequencies of the

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optical carrier and the modulation (±60 GHz) respectively. Hence, when the ROF signal is propagating in an optical fiber, fiber chromatic dispersion causes a differential delay to be progressively added to the sidebands and the carrier, causing RF fading. The signal is highly distorted after propagating of 100 km SMF. For the OCS signal, there are two dominant tones of $\omega_c - \omega_m/2$ and $\omega_c + \omega_m/2$. The OCS-ROF transmission is also limited by the code time-shifting by the two dominant tones. We can observe that the conventional SSB-ROF signal is only slightly distorted after propagating 100 km SMF, since the ROF signal is generated by the coherent beating between the center wavelength (dc component) and the 1st order lower-sideband. However, the immunity against chromatic dispersion depends on the suppression of other sidebands, hence tight optical filtering after the modulator is required. For the proposed SSB-ROF signal generation using ring-modulator, optical filter after the modulator is not required.

3. Fabrication of the silicon ring modulator

The silicon microring modulator used in the SSB generation was fabricated on a silicon-on-insulator (SOI) wafer with a 2 µm thick buried oxide layer (BOX). The width and the height of the optical waveguide are 500 nm and 340 nm respectively, with a slab thickness of 140nm to provide a conductive path between two electrodes. The cross section of the modulator is shown in Fig. 2(a). The silicon ring-modulator is based on a p-i-n diode structure under forward bias operation [13,14]. The carrier concentrations for the n+ and p+ slab region are around 2×10^{20} cm^{-3} and 6×10^{19} cm^{-3} respectively. Figures 2(b) and 2(c) shows the top view microscope photograph of the ring-modulator and the measured optical spectra of the silicon ring-modulator respectively. The optical spectra illustrate the shift of the resonant null towards shorter wavelength under different bias voltages. The DC extinction ratio produced by the modulator is >16 dB.

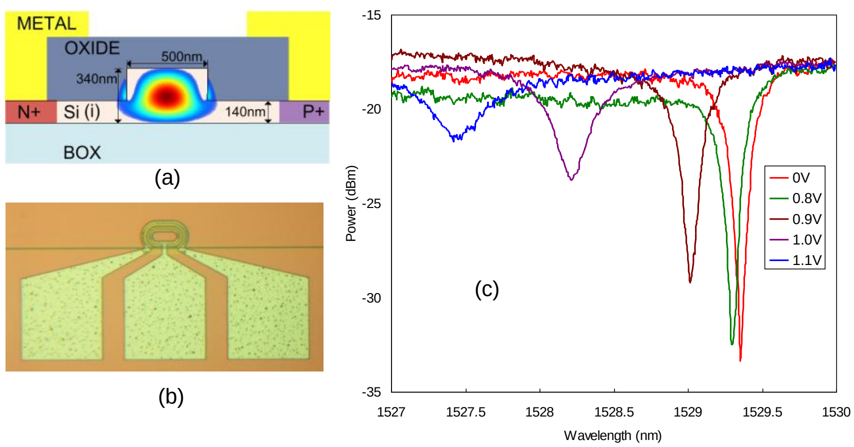

Fig. 2. (a) The cross section, (b) microscope photograph and (c) measured optical spectra of the silicon ring-modulator.

4. LR-ROF transmission experiment using SSB signal

Figure 3 shows the experimental setup of the generation and the transmission of the SSB signal. Two coherent optical tones of 60 GHz apart were first generated from the continuous wave (CW) signal by using a MZM. The MZM was driven by a 30 GHz sinusoidal signal. By biasing the MZM at 0.5 V_π, optical two tones with wavelength separation of 60 GHz were produced. The optical two tones were launched into the silicon ring-modulator, which was electrically driven by a 1 Gb/s NRZ data signal. One unique feature of the silicon ring-modulator was that it only modulates the signal wavelength located at the resonant null. This made it very suitable for encoding data on one of the sidebands of the optical two tones signal

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without the need of the separation of the sidebands. In the experiment, the shorter wavelength sideband was launched into the resonant null to produce the SSB-ROF signal. Using shorter wavelength sideband is because the resonant null of the modulator will shift to the shorter wavelength side when the applied voltage increases, as shown in Fig. 2. The modulator thus encoded the shorter wavelength sideband with 1 Gb/s data, while the longer sideband was still un-modulated.

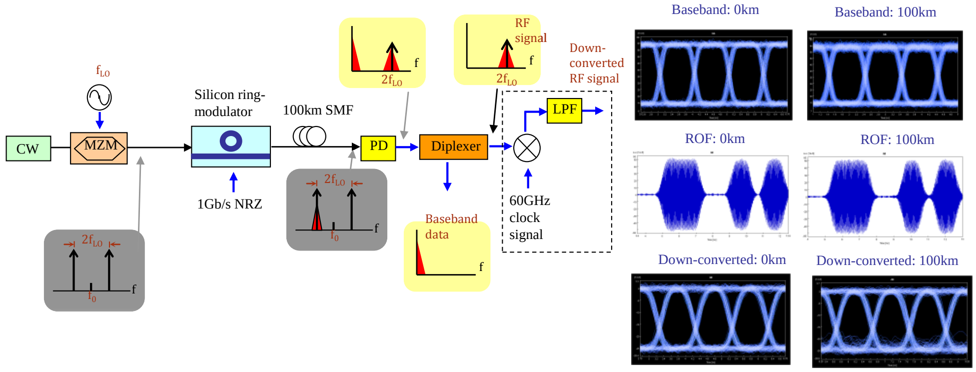

Fig. 3. Architecture of the LR-ROF transmission experiment using SSB signal. MZM: Mach-Zehnder modulator, PD: photodiode, LPF: low pass filter. Inset: simulated time-domain patterns and eye-diagrams at 0 km and 100 km of the SSB-ROF signals.

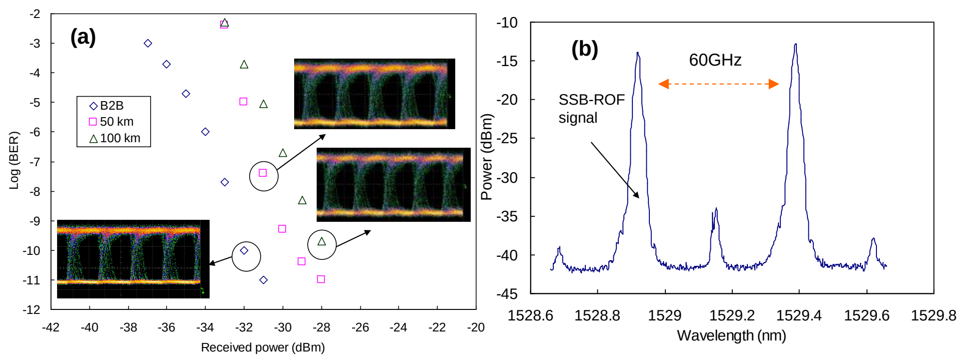

Fig. 4. (a) Measured BER performances of the baseband NRZ signals generated by the self-beating at the PD in the LR-ROF network. Insets: corresponding eye diagrams. (b) Measured optical spectrum of the SSB-ROF signal generated by the silicon ring-modulator.

The signal was then transmitted through 0 km (back-to-back, B2B), 50 km and 100 km standard SMF without dispersion compensation before being launched into a photodiode (PD) in the RAU. At the PD, the self-beating of the NRZ data will produce the baseband signal while the coherent beating between the two optical sidebands will produce the RF signal at 60 GHz frequency band. An electrical diplexer can be used to separate the baseband data for PON applications, while the RF signal can be directly emitted via an antenna or RF down-converted to baseband for analysis. The simulated baseband, ROF and RF down-converted signals at 0 km and 100 km transmission are shown in insets of Fig. 3. We can observe a high quality of ROF signals can be achieved even propagating through 100 km SMF without dispersion compensation in this scheme. This is because the ROF signal is generated by the coherent beating between the CW and data-carrying sideband, and the RF power fading effect and the code time-shifting effect occurring in DSB and OCS ROF signals can be mitigated.

Figure 4(a) show the bit-error rate (BER) performance of the baseband NRZ signal generated by the self-beating of the higher wavelength sideband at the PD in the LR-ROF network. We measured ~2.5 dB power penalties in the 50 km SMF transmission and an

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additional of 1.5 dB power penalties in the 100 km SMF transmission. BER of $<10^{-9}$ can be measured in all cases without error-floor. Insets show the corresponding baseband eye-diagrams. Figure 4(b) show the measured optical spectrum (resolution of 0.01 nm) of the SSB-ROF signal generated by the silicon ring-modulator, showing the two optical sideband have similar magnitude, hence can producing high modulation depth ROF signal. It also has a high center wavelength suppression of > 20 dB.

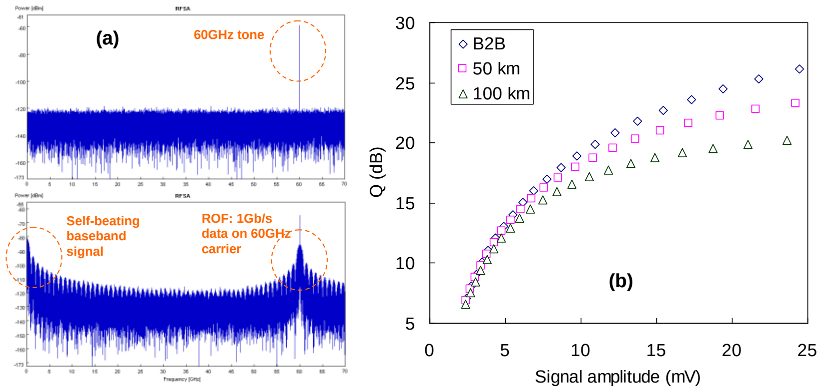

Fig. 5. (a) Simulated RF spectra of the generated 60 GHz RF signal without (upper graph) and with (lower graph) applying the electrical NRZ data to the silicon ring-modulator. (b) Simulated Q-values (dB) of the RF down-converted signal against different signal amplitudes.

Due to the unavailability of a 60 GHz RF measurement system, simulations using VPI Transmission Maker were performed to evaluate the 60 GHz ROF signal. Figure 5(a) shows simulated RF spectra (resolution of 100 kHz) of the generated 60 GHz RF signal without (upper graph) and with (lower graph) applying the electrical NRZ data to the silicon ring-modulator. We can observe that the 1 Gb/s NRZ signal can be successfully encoded onto the 60 GHz carrier. The self-beating NRZ signal at baseband can also be observed. Figure 5(b) shows the simulated Q-values (dB) of the RF down-converted signal using the RF mixer and 60 GHz sinusoidal signal (shown in the dotted box in Fig. 3) against different signal amplitudes launching into the signal analyzer. Results show that error-free (Q > 15 dB) SSB-ROF LR transmissions can be achieved without dispersion compensation.

5. Conclusion

The integration of the LR-PON and the LR-ROF is a promising architecture in future networks. Here we proposed and experimentally demonstrate a LR-ROF signal distribution using SSB-ROF signal generated by a silicon ring-modulator. The unique feature of the silicon ring-modulator allows the generation of the SSB-ROF signal in an easy and convenient way. Numerical comparison of the SSB-ROF with the DSB-ROF and OCS-ROF signals and the fabrication of the silicon ring-modulator were discussed. Due to the coherent beating between the CW and data-carrying sideband, the generated SSB-ROF signal can mitigate the periodic RF power fading effect and the code time-shifting effect occurring in DSB and OCS ROF signals. We showed that high quality of ROF signals can be propagating even over 100 km SMF without dispersion compensation.

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