6-GHz Radio-Over-Fiber Upstream Transmission Using a Directly Modulated RSOA

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***Abstract*—We propose and demonstrate 40-km upstream transmission of a 2-Gb/s 6-GHz binary phase-shift keyed radio signal using a directly modulated reflective semiconductor optical amplifier (RSOA). A delay interferometer, acting as an optical equalizer, compensates for limited RSOA modulation bandwidth and simultaneously performs single sideband filtering to relieve dispersion-induced radio-frequency (RF) fading effect. Furthermore, extended transmission distance of up to 40 km is shown to be made possible by reduced Rayleigh backscattering-induced crosstalk.**

***Index Terms*—Chirp modulation, equalizers, radio over fiber (RoF), semiconductor optical amplifier (SOA).**

I. Introduction

RADIO over Fiber (RoF) systems, thanks to their format transparency and compact realization of remote base stations (RBSs), have long been regarded as a promising solution for broadband wireless backhaul networks [1], [2]. The RBSs can be implemented simply by using a laser diode (LD), an optical modulator, an optical receiver, electrical amplifiers, and antennas. From a view point of improving the reliability of the systems and reducing the maintenance cost of failure-prone LDs at the RBSs, it is highly desirable for service providers to move the light sources to a centralized location. Reflective semiconductor optical amplifiers (RSOAs) seeded by an optical carrier from the central office (CO) have been exploited for reliable RBSs of such networks [3]–[6]. Here, the continuous wave seed light from the CO first traverses the transmission fiber and is fed to the RSOA for upstream modulation. The directly modulated RSOA signal is then sent back to the CO for detection. However, all previously reported RoF systems using RSOAs have operated at $\leq$1 GHz [3], [4]. This is because the modulation bandwidth of RSOAs is limited by the carrier lifetime in the active layer and is less than 3.5 GHz [3]. To circumvent the bandwidth limitation of the devices, some RoF systems utilized frequency down-conversion of wireless signals to baseband before being fed to RSOA [5]. This requires additional signal processing circuitry at RBSs, increasing cost and complexity. Other technique to avoid the frequency down-conversion includes the use of optical envelope detection by RSOA [6]. This technique is, however, applicable only to wireless signals with amplitude modulation formats when the carrier frequency is larger than the modulation bandwidth of RSOA, depriving advantages of advanced modulation formats such as quadrature phase-shift keying.

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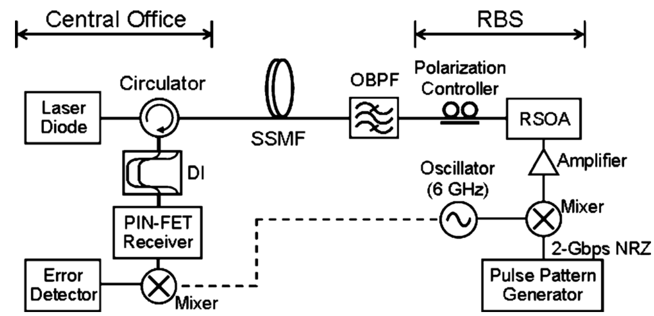

Fig. 1. Experimental setup.

In this letter, we propose and demonstrate a 40-km upstream transmission of a 6-GHz binary phase-shift keying (BPSK) radio signal using a directly modulated RSOA in a single-fiber loopback network. To the best of our knowledge, this is the longest transmission distance and also highest radio frequency (RF) carrier frequency carried over a directly modulated RSOA in a directly-detected loopback-configured network. We utilize a delay interferometer (DI) to equalize the band-limitation of the RSOA [7]. Not only does the passive optical device enhance the bandwidth of the system, but it also helps to generate optical single sideband (SSB) signals to make them robust against fiber dispersion. Octave confined radio-over-fiber transmission greatly reduces the Rayleigh backscattering-induced crosstalk to extend the transmission distance.

II. Experiment and Results

Experimental setup is depicted in Fig. 1. A continuous wave LD operating at 1550.14 nm was first launched into standard single-mode fiber (SSMF) through an optical circulator and then fed to an RSOA. The RSOA used in the experiment is housed in a transistor-outlook (TO)-can package and is an uncooled device. The polarization-dependent gain of the device was measured to be 2.5 dB and thus we inserted a polarization controller before the RSOA. In real systems, use of polarization-insensitive RSOAs can eliminate the polarization controller. A 2-Gb/s nonreturn-to-zero (NRZ) signal (pseudorandom bit sequence length of $2^{31}-1$) was converted into a 6-GHz BPSK signal at a mixer and then directly modulated the RSOA. The bias current of the RSOA was set to 41 mA. The 3-dB modulation bandwidth of the RSOA was 1.2 GHz. The signal was sent back to the SSMF, fed to a DI, and directly detected by a PIN receiver at the CO. The free-spectral range of the DI was

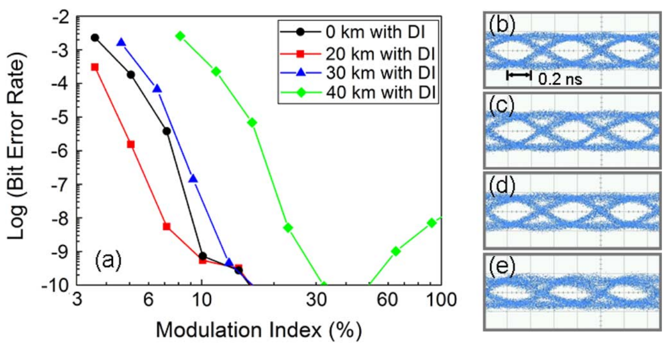

Fig. 2. (a) Measured BER as a function of OMI for 0-, 20-, 30-, and 40-km transmission over SSMF. Plotted on the right are electrical eye diagrams measured at the receiver after (b) back-to-back transmission at 40.2% OMI, (c) 20-km transmission at 40.2% OMI, (d) 30-km transmission at 36.6% OMI, and (e) 40-km transmission at 45.5% OMI.

25 GHz. In the transmission link, we have an optical band-pass filter (OBPF) with a bandwidth of 1.5 nm to emulate a waveguide grating router at the remote node. The received electrical RF signal is mixed with a 6-GHz oscillator in a coherent homodyne demodulation and fed into an error detector for bit-error rate (BER) measurement. Due to lack of carrier recovery circuit, we utilized a single oscillator for both BPSK modulation and demodulation.

We first try to measure the BER for 20-km transmission without using the DI. We had complete eye closure and were not even able to recover the clock, confirming severe bandwidth limitation of the RSOA. BER measurement is repeated with the DI being placed before the receiver for 0-, 20-, 30-, and 40-km transmission. Fig. 2 shows the measured BER as a function of the root-mean-square optical modulation index (OMI) of the signal measured at the output of the DI. The injection power of the seed light into the RSOA was -6.0, -6.0, -8.1, and -10.6 dBm for 0, 20, 30, and 40 km, respectively. For 0- and 20-km transmission, the RSOA was biased at 41 mA. Since the effects of Rayleigh back-scattering increases with fiber length, the RSOA gain was reduced by lowering its bias current as the transmission distance increases. For example, the bias was set to be 34 and 30 mA for 30- and 40-km fibers, respectively. The DI is adjusted to maximize eye opening and to minimize BER. The optical power measured at the receiver was -9.1 dBm for back-to-back transmission. The results in Fig. 2 show that we achieve a BER lower than 10^{-9} when the OMI is $>20\%$ for 0, 20, and 30 km. At these lengths, no BER degradation was observed even at a large OMI of 100%. Compared to the back-to-back measurement, we have slight improvement of BER performance after 20-km transmission. We ascribe this to the SSB filtering of the DI combined with the chirp of the RSOA [7]. For 40-km transmission, however, we have an OMI penalty of 3.5 dB with respect to the back-to-back measurement. Performance degradation caused by clipping effects and nonlinear light-versus-current characteristics of the RSOA is observed for 40-km transmission in excess of 40% OMI. Nevertheless, the electrical eye diagrams measured at the receiver [Fig. 2(b)–(e)] confirm the successful transmission up to 40 km.

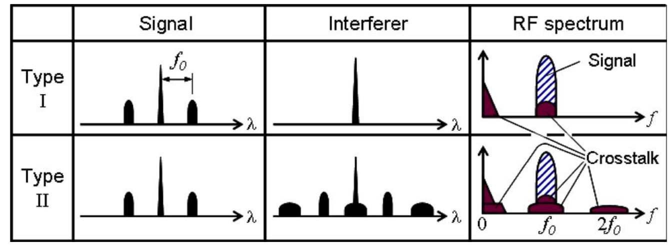

Fig. 3. Effects of Rayleigh backscattering in radio-over-fiber systems. For simplicity, chirp-induced spectral broadening is not taken into consideration.

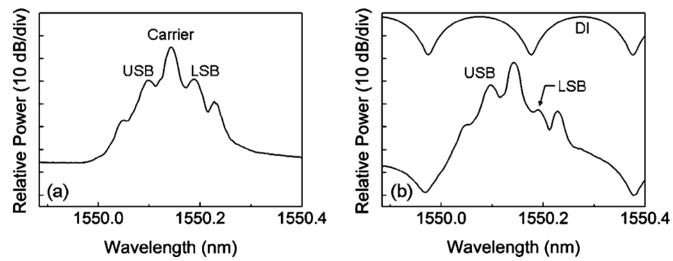

Fig. 4. Optical spectra of the signal (a) before the DI and (b) after the DI. The transmittance of the DI is also depicted in (b). They are measured with an optical spectrum analyzer (resolution $= 0.02$ nm). The fiber length is 20 km and the OMI is 40.2% for the signal spectra.

In a single-fiber loopback network, Rayleigh backscattering-induced crosstalk can limit the maximum reach in two ways: Rayleigh backscattered seed light interferes with the upstream data signal (type I) and Rayleigh backscattered upstream data signal is modulated again by RSOA and interferes with the upstream data signal (type II) [8]. Compared to baseband transmission, the deleterious effects of both type-I and type-II crosstalk are greatly reduced. As illustrated in Fig. 3, low-frequency Rayleigh crosstalk of type I, which extends from zero frequency to several MHz at the receiver and accounts for 50% of the crosstalk, does not affect the high-frequency radio signal [9]. A large amount of type-II crosstalk also falls outside the radio signal band at the receiver when the signal is confined within an octave.

Fig. 4 shows the optical spectra of the signal measured before and after the DI. Also depicted in the figure is the transmittance of the DI. Direct modulation of RSOA by the 6-GHz radio signal produces two small sidebands around the optical carrier, as shown in Fig. 4(a). The null frequency of the DI is located 4.2 GHz off the LD frequency. Thus, it filters out the lower-frequency sideband (LSB) of the RSOA output, leaving the upper-frequency sideband (USB) and thus making an SSB signal. Fig. 4(b) shows the optical spectrum of the signal measured at the output of the DI. The LSB of the signal is suppressed by $\sim$10 dB compared to the USB after the DI.

To demonstrate that our proposed scheme successfully generates optical SSB signals and does not suffer from dispersion-induced RF fading, we measure the RF power of a 6-GHz sinusoidal wave in the presence of fiber chromatic dispersion and plot the results in Fig. 5. To isolate the dispersion effects from others without changing the injection power into the RSOA, we modified the measurement setup as shown in the inset of Fig. 5. The injection power of the seed light into the RSOA is kept

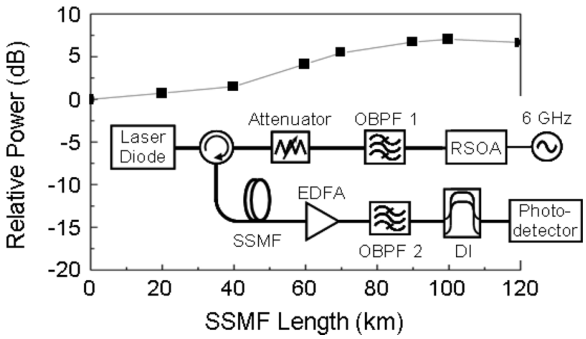

Fig. 5. Relative RF power of a 6-GHz sinusoidal wave as a function of transmission distance over SSMF. The inset shows the measurement setup.

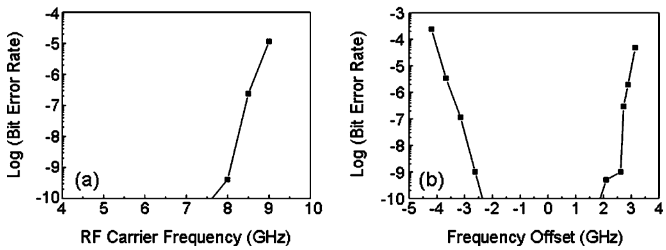

Fig. 6. (a) Measured BER versus the RF carrier frequency after 20-km transmission. (b) BER versus the frequency offset between the DI and LD when the RF carrier frequency is 6 GHz.

-6 dBm throughout this measurement. The RSOA is directly modulated with a 6-GHz sinusoidal wave and sent to SSMF for transmission. An Erbium-doped fiber amplifier is employed after transmission to compensate for the fiber loss. An OBPF (i.e., OBPF 2 in the inset) is used to reject the amplified spontaneous noise and thus to minimize the contribution of the noise when calibrating the received signal power. The optical power into the DI is kept -7 dBm. The figure shows that the signal power at the detector is fairly constant with a small variation of 7.0 dB over 120 km. The power variation should be attributed to a finite sideband suppression ratio (SSR). Theoretical calculation shows that a 10-dB SSR leads to 5.7-dB fluctuations of the received RF power in the presence of dispersion [10], which agrees with our measurement. Also shown in the figure is that maximum RF power, which is indicative of constructive interference between two beat signals, carrier-USB and carrier-LSB, is achieved at 100 km instead of at 0 km. This is because the optical signal is prechirped as the spectral components had a relative phase shift at 0 km.

Fig. 6(a) shows the measured BER versus the RF carrier frequency after 20-km transmission. The received optical power was -9.1 dBm. The OMI of the signal is set to 40.2% at 6 GHz and kept unchanged throughout this measurement. We have a BER $< 10^{-10}$ for RF carrier frequencies from 4.0 to 7.5 GHz. Due to the limited bandwidth of the system, the BER deteriorates rapidly when the RF carrier frequency exceeds 8 GHz.

Fig. 6(b) shows the frequency offset tolerance between the LD and DI. Here, zero frequency offset refers to the case when the null frequency of the DI is located 4.2 GHz off the LD frequency. The RF carrier frequency was 6 GHz and the received optical power was -9.1 dBm. It is found that the frequency offset should be kept within ± 2 GHz to have a BER less than 10^{-9}. Since both the seed light and the DI can be located in the same place (e.g., CO), the frequency alignment could be achieved by locking the seed light wavelength to the DI [7].

It is worth mentioning that thanks to periodicity of DI transmittance a single DI can be used for multiple channels in wavelength-division multiplexed (WDM) RoF systems. Especially, a 25-GHz DI can be used in a set-and-forget mode to equalize multiple WDM channels anchored at the 100-GHz spaced frequency grid [11].

III. Conclusion

We have proposed and demonstrated upstream transmission of a 2-Gb/s, 6-GHz radio signal over a 40-km loopback-configured network using a directly modulated RSOA packaged in a TO-can. Use of DI greatly improves the system bandwidth as well as dispersion tolerance, and thus allows us to exploit 6-GHz radio signals for transmission. The Rayleigh backscattering-induced crosstalk is greatly reduced by employing the high-frequency, octave-confined radio signal. By virtue of these, we successfully demonstrate 40-km transmission of the 6-GHz radio signal in a single-fiber loopback network without any forward error correction.

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