Bidirectional radio-over-fiber systems with SSB modulation and wavelength reuse based on injection-locked semiconductor lasers

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A 60-GHz bidirectional radio-over-fiber (RoF) system using two-carrier-injected distributed feedback (DFB) laser is proposed and demonstrated to realize optical single sideband (SSB) modulation for downlink. An injection-locked Fabry-Pérot laser is also carried out to realize wavelength reuse in uplink. Transmission of 2.5 Gb/s on a 60-GHz carrier for downlink and 622-Mb/s baseband signal for uplink are both successfully demonstrated over 50-km single mode fiber without chromatic dispersion compensation.

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Radio-over-fiber (RoF) technology has been an attractive innovation in high-speed wireless access network supporting many kinds of applications. Much attention has been paid on the 60-GHz-band RoF system due to its ultra wide bandwidth[1−4]. When carrier frequency goes up to dozens of gigahertz, it is significant to share the up-conversion equipment with several base stations (BSs) to reduce network cost. Optical heterodyne technique, which delivers two phase-correlated optical modes from the central station and converts them to the electrical signal in the BS, can easily share the up-conversion equipment among the BS. To further reduce the cost of BS, several schemes of RoF systems using centralized light source have been proposed[5−9]. In such architecture, the downstream wavelength is reused at the BS in order to re-modulate upstream data. The same wavelength operation has been used for both downstream and upstream, and source-free BS can be realized in such RoF systems. In RoF systems with optical heterodyning for the generation of millimeter-wave(mm-wave), optical single sideband (SSB) modulation has been used to mitigate power fading resulting from the chromatic dispersion of the fiber. The non-modulated of the two phase-correlated optical carriers can be used as the light source for uplink. Many SSB modulation techniques have been proposed to solve this problem[10−15]. Previously, we have demonstrated a new approach of SSB modulation in optical heterodyning mm-wave RoF systems using injection-locked semiconductor laser[16]. In this letter, we propose a bidirectional 60-GHz RoF system using a two-mode-injected distributed feedback (DFB) laser to realize SSB modulation for the downlink. An injection locked Fabry-Pérot (FP) laser is used to realize wavelength reuse for uplink. The transmission of 2.5 Gb/s on a 60-GHz carrier for downlink and 622-Mb/s baseband signal for uplink are successfully demonstrated over the 50-km standard single mode fiber (SMF) using the proposed system.

The experimental setup of bidirectional RoF system is shown in Fig. 1. A tunable laser at 1550.78 nm was modulated by a $LiNbO_3$ Mach-Zehnder modulator (MZM) with 30-GHz radio frequency (RF) signal. The MZM was biased at the switching voltage V_π to produce optical carrier suppression modulation. An optical interleaver was used to select the two first-order modulation sidebands and to reject the undesired optical carrier. An erbium-doped fiber amplifier (EDFA) was used to supply enough power for injection locking. The two modes with 60-GHz spacing and 5-dBm total power were injected into a DFB laser through a three-port optical circulator. Only one mode was tuned to lock the DFB laser. The DFB laser had a threshold current of 14 mA and was biased at 25 mA. The 2.5-Gb/s pseudorandom binary sequence (PRBS, $2^{31}-1$) non-return-to-zero (NRZ) signal from a pattern generator was used to modulate the DFB laser. When the DFB laser was directly modulated by the downlink data, the locked mode was strongly modulated, whereas the other mode was almost not modulated[14]. A polarization controller was introduced to align the polarization state of input light with that of the DFB laser. After 50-km SMF transmission, an EDFA was used to compensate transmission loss and supply enough power for injection locking in downlink. The received optical signal was divided into two parts by an optical coupler. One part was detected by a photodiode with 3-dB bandwidth of 70 GHz. The received 60-GHz subcarrier signal was frequency down-converted to the baseband with a mixer and a 60-GHz local oscillator. The recovered 2.5-Gb/s signal was used to measure bit error rate (BER). Another part was fed onto an optical filter and the non-modulated optical mode was filtered out for the injection-locked FP laser for uplink. The injection power was −10 dBm. The 622-Mb/s, $2^{31}-1$, PRBS NRZ signal was used for the direct modulation of the injection-locked FP laser. Optical injection locking was maintained by controlling the temperature of the DFB and FP lasers.

Figure 2(a) compares the optical spectra of the locked DFB laser with and without modulation. The longer wavelength mode at 1551.0 nm is used for this purpose. When the DFB laser is directly modulated, the

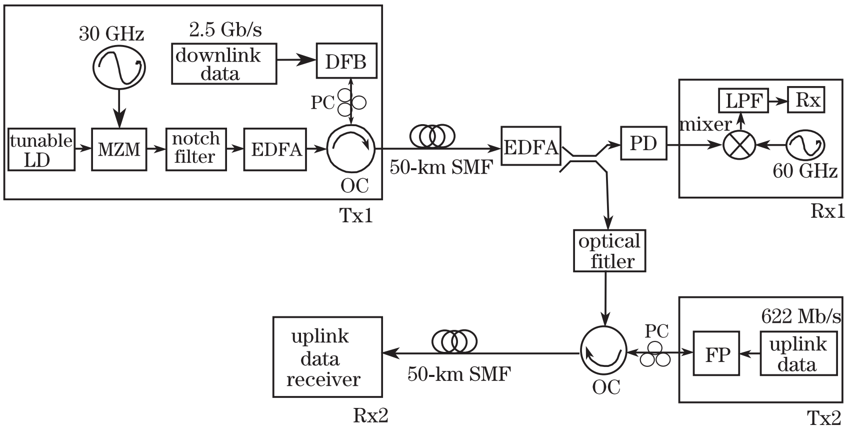

Fig. 1. Experimental setup of bidirectional RoF system based on injection locked lasers. PD: photodiode; PC: polarization controller; LPF: low pass filter; OC: optical circulator; Tx: transmitter: Rx: receiver.

injection-locked mode is modulated and its spectrum broadens, whereas the unlocked mode stays almost the same during modulation.

The locked slave laser can be recognized as a gain-clamped amplifier with its cavity mode red-shifted[17]. The red-shifted cavity mode supplies an optical gain to the modulation sidebands. The center wavelength of the optical gain profile can be controlled by injection power and frequency detuning. Small injection power and negative frequency detuning can lead to a cavity mode close to the injection-locked mode.

In our experiment, the slave laser was directly modulated at 2.5 Gb/s. It generated two sidebands on both upper and lower sides of the injection-locked mode. The injection power of 5 dBm and frequency detuning of −2.5 GHz were chosen to move the red-shifted cavity mode close to the locked modes. Thus, the modulation sidebands can be resonantly amplified. In more detail, the longer-wavelength sideband is closer to the cavity mode compared with the shorter-wavelength sideband, so it is more amplified. The unlocked mode, which was 60 GHz away from the locked mode, was beyond the gain range of the cavity mode and its modulation sidebands cannot be amplified. Direct modulation of the slave laser caused large modulation index difference between the two modes for small injection power and negative frequency detuning.

Figure 2(b) shows the spectra of the FP laser before and after injection locking. Injection locking results in over 30-dB side-mode suppression ratio (SMSR) for the FP laser. By adjusting the wavelength downstream, several FP modes, from 1540 to 1560 nm, can be locked separately with −10-dBm injection power, hence realizing the colorless operation of the proposed system.

Figure 3 shows the RF spectra of the 60-GHz signal after downlink data modulation. After 50-km SMF transmission, the measured BER curves for downstream and upstream link are obtained, as shown in Figs. 4(a) and (b), respectively. Downlink and uplink suffer 2 and 0.25-dB power penalty compared with the back-to-back (BTB) case. For the downlink, the penalty is due to the residual dispersion of the SSB modulation. For the uplink, there is 1-dB power penalty when the downlink modulation is set on, as the unlocked mode used for injection locking the FP laser is slightly modulated by the downstream data, thereby introducing a cross-talk on the upstream.

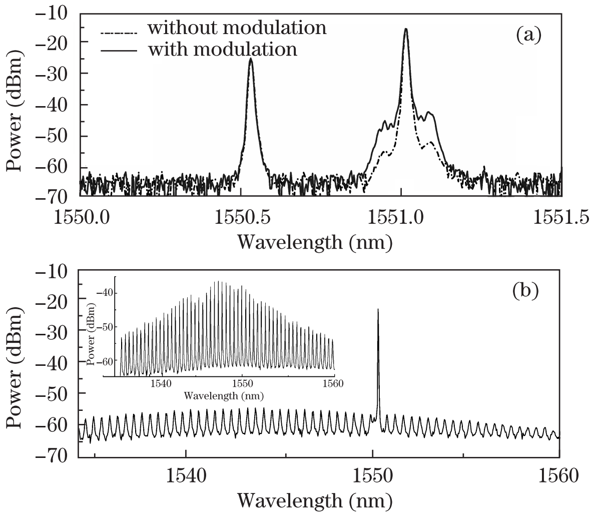

Fig. 2. Optical spectra of (a) injection-locked DFB laser with and without modulation and (b) injection-locked FP laser. Inset: free-running FP laser.

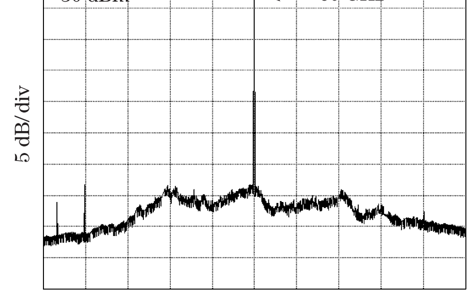

Fig. 3. RF spectra of 60 GHz. The measurement range of our electrical spectral analyzer is limited to 40–60 GHz. The RF signal higher than 60 GHz has lower and more irregular response. Resolution bandwidth: 1 MHz

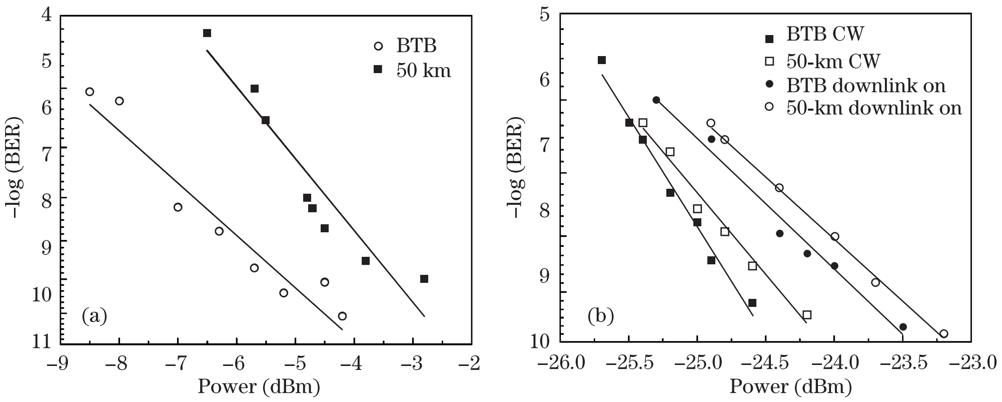

Fig. 4. Measured BER of (a) downlink and (b) uplink. "CW" marks the BER for uplink when downlink data is not modulated on the DFB laser.

In conclusion, we propose and experimentally demonstrate a bidirectional RoF system based on injection locked semiconductor lasers. For the downlink, optical SSB modulation is generated by a two-mode injected DFB laser. For the uplink, an injection-locked FP laser used as a modulator achieves high SMSR for good transmission performance; it can also realize colorless operation. Both the 2.5-Gb/s signal on 60-GHz downlink and 622-Mb/s uplink are successfully transmitted over 50-km SMF.

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