Optical Frequency-interleaving Full-duplex Technique for Fiber-optic Transmission of Millimeter-wave-band Frequency-modulated Continuous-wave Downlink Signal and 10-Gb/s On-off-keying Uplink Signal

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Abstract— An optical frequency-interleaving full-duplex technique for fiber-optic transmission of millimeter-wave-band frequency-modulated continuous-wave downlink signal and 10-Gb/s on-off-keying uplink signals is newly proposed. The proposed full-duplexing technique with a flexible wavelength channel selector is experimentally demonstrated.

1. INTRODUCTION

High-precision imaging technology has been in strong demand for safety and security at important facilities. For example, for runway monitoring, several-inch class debris should be detected and removed to ensure safe takeoff and landing [1]. To achieve such high-precision imaging by radio, millimeter-wave (mm-wave) is a promising candidate because of its broad transmission bandwidth. To overcome the large propagation loss and atmospheric attenuation in the mm-wave bands, the introduction of a distributed antenna system (DAS) concept is necessary for large-area surveillance. In the DAS, radio-over-fiber (RoF) technology aids in realizing easy radio signal distribution with a low-loss optical fiber. We have demonstrated the optical generation for highly accurate frequency-modulated continuous-wave (FM-CW) signal, which has high affinity with the RoF technology [2]. We have also demonstrated the distribution of FM-CW signals with three different frequency band in a wavelength division multiplexing (WDM) RoF system [3, 4]. In the demonstrations, although the downlink transmission of FM-CW signals has been verified, an uplink transmission for sending sensed data back to a central control station (CCS) has never been considered.

In this paper, we investigate an optical frequency-interleaving full-duplex technique for fiber-optic transmission of mm-wave-band FM-CW downlink signal and 10-Gb/s on-off-keying (OOK) uplink signal. Their optical duplexing is experimentally demonstrated with a flexible wavelength channel selector for two cases of downlink mm-wave-band, that is, 96-GHz-band and 48-GHz-band.

2. SYSTEM CONCEPT

Figure 1 shows the conceptual diagram of a proposed optical frequency-interleaving full-duplex technique for fiber-optic transmission of both an FM-CW signal for the downlink and an OOK signal for the uplink.

The system with the proposed technique basically consists of a sub-harmonic FM-CW source, a proposed fiber-optic full-duplex link, a sensed data analyzer, an electrical multiplier, an electrical

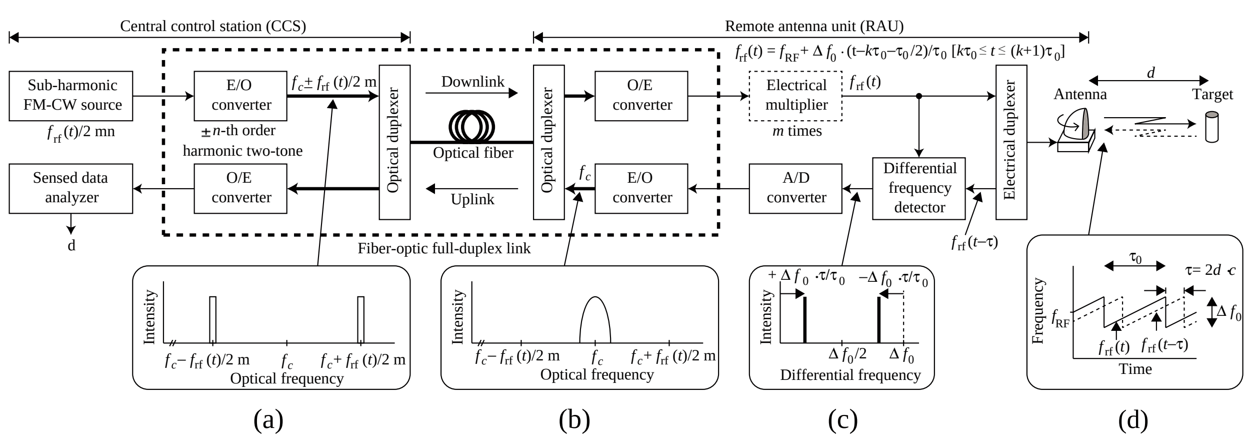

Figure 1: Conceptual diagram of a proposed optical frequency-interleaving full-duplex technique for fiber-optic transmission of both an FM-CW signal for the downlink and an OOK signal for the uplink.

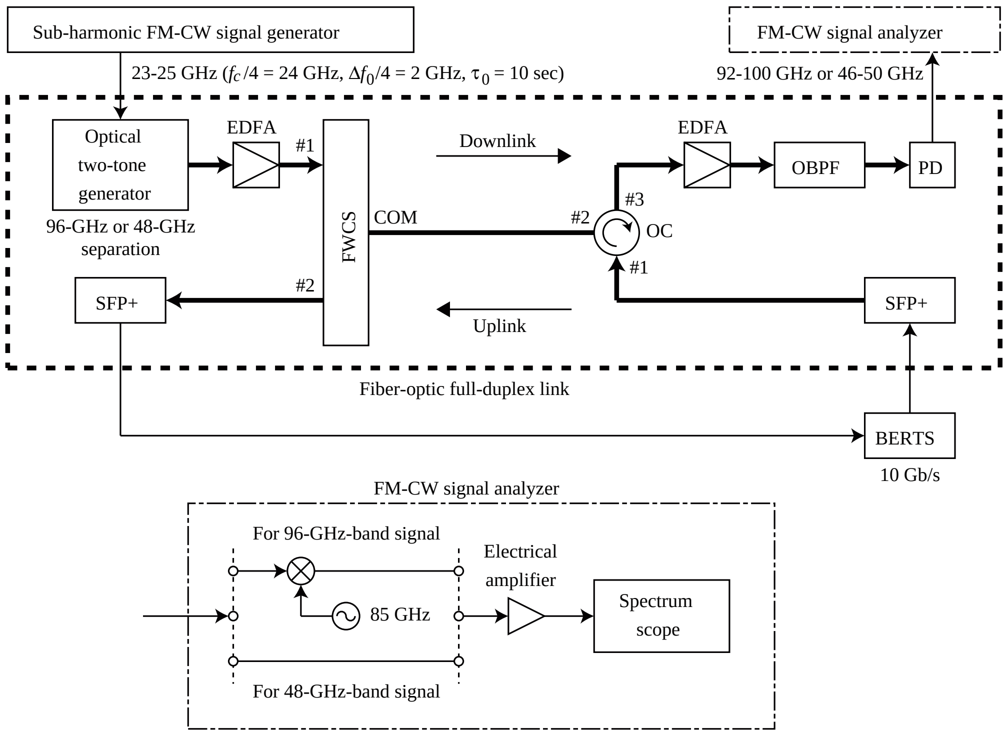

Figure 2: Experimental setup.

duplexer, a mm-wave-band antenna, a differential frequency detector, and an analog-to-digital (A/D) converter. The proposed fiber-optic full-duplex link fundamentally consists of two pairs of electrical-to-optical (E/O) and optical-to-electrical (O/E) converters, two optical duplexers, and an optical fiber. For the downlink, at first, a sub-harmonic FM-CW signal, $f_{rf}(t)/2mn$, is generated as a driving signal of the E/O converter in a central control station (CCS). Here, m represents the multiple number of the electrical multiplier. As mentioned in Section 1, no electrical multiplier is necessary for the case that the output of the O/E converter is a desired-frequency-band FM-CW signal. The E/O converter generates a desired $\pm n$-th order harmonic optical two-tone signal with the sub-harmonic FM-CW signal, $f_c \pm f_{rf}(t)/2m$, which is a kind of RoF signal as shown in Figure 1(a) [4–6]. The RoF signal passes through the first optical duplexer and then is transmitted to a remote antenna unit (RAU) over the optical fiber. In the RAU, the received RoF signal after passing through the second optical duplexer is put into the O/E converter. The output of O/E converter is multiplied by m with the electrical multiplier to generate a desired-frequency-band FM-CW signal, $f_{rf}(t)$. The generated FM-CW signal is radiated from the antenna to detect a target. As an example, a saw-tooth FM-CW signal with the frequency transition of Δf_0 and the repetition time of τ_0 at the center frequency of f_c is shown in Figure 1(d). In this case, $f_{rf}(t)$ is written as $f_{RF} + \Delta f_0 \cdot (t - k\tau_0 - \tau_0/2)/\tau_0$ $[k\tau_0 \le t \le (k+1)\tau_0]$, where f_{RF} represents a central carrier frequency of FM-CW signal. In our system, it is assumed that f_{RF} is mm-wave band and Δf_0 is GHz-class for the detecting several-inch class debris. In the downlink system, therefore, the E/O and O/E converter should have mm-wave-band interfaces. For the uplink system, the FM-CW signal reflected from the target, $f_{rf}(t-\tau)$, is received at the antenna, where τ $[= 2d \cdot c]$ represents a transmission delay in proportion to a measurement distance between the antenna and the target, d, with the velocity of light in the vacuum, c. As shown in Figure 1(c), a differential frequency between the transmitted and received FM-CW signals, $\Delta f_0 \cdot \tau/\tau_0$ or $\Delta f_0 \cdot (1 - \tau/\tau_0)$, can be detected with the differential frequency detector as a sensed data. The detected differential frequency component is digitized with the A/D converter. Then the sensed data at the optical carrier frequency of f_c as shows in Figure 1(b) is sent back to the CCS over a conventional digital baseband fiber-optic link. Note that the baseband uplink signal is allocated inside of the FM-CW RoF downlink signal to enhance optical spectrum efficiency with a frequency-interleaving technique, which is our proposal. Finally, the sensed data after passing through the optical duplexer is analyzed to obtain the distance, d. In the system concept shown above, it is also noted that the fiber-optic full-duplex link must simultaneously handle both an analog downlink signal and a digital uplink signal.

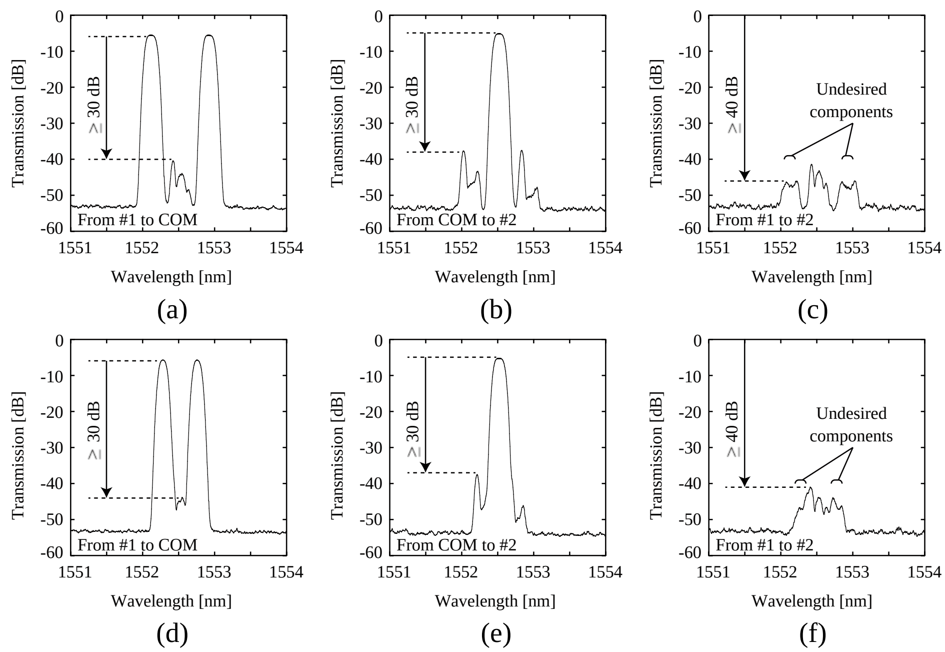

Figure 3: Measured transmission characteristics of FWCS: (a)–(c) for 96-GHz-band signal transmission and (d)–(f) for 48-GHz-band signal transmission.

3. EXPERIMENTAL DEMONSTRATIONS

In this paper, we concentrate on investigating the performance of the fiber-optic full-duplex link. The experimental setup is shown in Figure 2. The setup basically consists of a sub-harmonic FM-CW signal generator, an FM-CW signal analyzer, a bit error rate test set (BERTS), and a fiber-optic full-duplex link. The fiber-optic full-duplex link consists of an optical two-tone generator, two Erbium-doped fiber amplifiers (EDFAs), a flexible wavelength channel selector (FWCS), an optical circulator (OC), an optical band-pass filter (OBPF), a photo-detector (PD), an FM-CW signal analyzer, and two small form-factor pluggable plus (SFP+). To concentrate on investigating our proposed optical frequency-interleaving full-duplex technique, in this experiment, a long-distance optical fiber between the CCS and the RAU was omitted. For the downlink, the sub-harmonic FM-CW signal generator generated a sub-harmonic FM-CW signal, whose frequency swept from 23 to 25 GHz with the repeating time of 10 μsec. In the same manner as the optical modulation scheme shown in Refs. [5, 6], a RoF signal carrying a 96- or 48-GHz-band FM-CW signal at the center of 1552.5 nm was generated with the optical two-tone generator. The RoF signal was transmitted to the RAU via the FWCS. The FWCS is based on a wavelength selective switch and works as the first optical duplexer. In the RAU, the received RoF signal after passing through the OC was amplified and then detected to generate the desired 96- or 48-GHz-band FM-CW signal. Here, the OC works as the second optical duplexer. The FM-CW signal was put into the FM-CW signal analyzer to measure the spectrogram. Due to the limited bandwidth of spectrum-scope, the 96-GHz-band signal was down-converted to an 11-GHz-band signal. For the uplink, the first SFP+ generated an optical OOK signal carrying a 10-Gb/s data at the carrier wavelength of 1552.5 nm, where the data had a 31-bit pseudo random bit sequence (PRBS) pattern. Note that the OOK uplink signal was allocated inside of the FM-CW RoF downlink signal. The optical OOK signal was duplexed with the downlink RoF signal by using the OC and then sent back to the CCS. The received optical OOK signal after passing through the FWCS was put into the second SFP+ to regenerate the 10-Gb/s data. Finally, a bit error rate (BER) of the regenerated data was measured with the BERTS.

First, we measured the fundamental transmission characteristics of FWCS for the purpose of optical duplexer. Figure 3 shows the measured transmission characteristics of the FWCS used in the experiment for both downlink and uplink directions. In this measurement, the direction from port #1 to port COM represents the downlink and the direction from port COM to port #2 represents the uplink. In addition, the measured spectrum for the direction from port #1 to port #2 represents a leakage of the signal put into port #1 for port #2. As shown in Figure 3, the

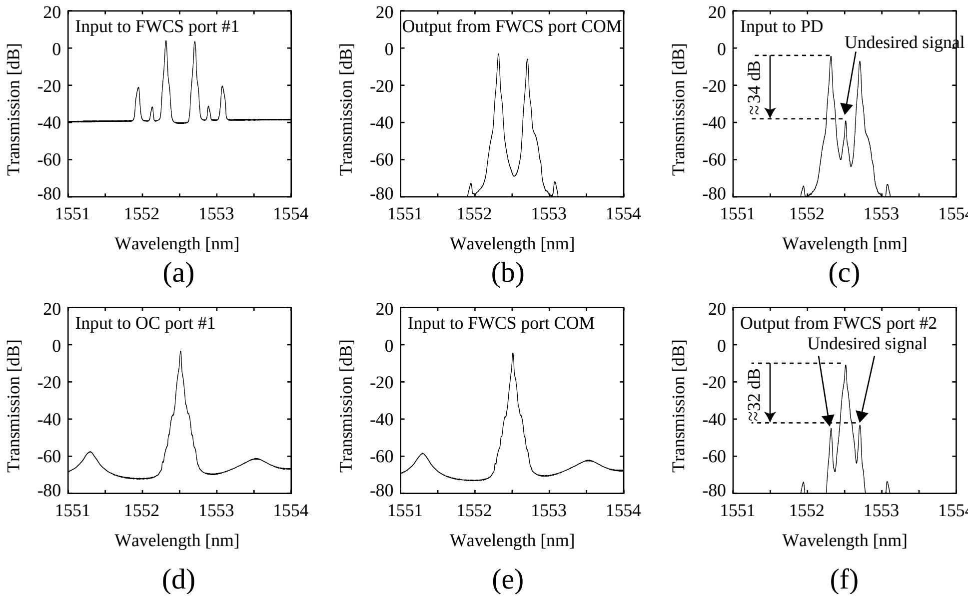

Figure 4: Measured spectra of (a)–(c) 48-GHz-band FM-CW RoF downlink signal and (d)–(f) 10-Gb/s OOK uplink signal.

insertion loss of FWCS was less than 6 dB. The desired frequency components were clearly obtained with the suppression ratio of more than 30 dB to undesired components and the leakage was less than −40 dB for both directions.

Next, we measured the de-multiplexing performance of FWCS with a 48-GHz-band FM-CW RoF signal for the downlink and a 10-Gb/s optical OOK signal for the uplink. Figure 4 shows the measured spectra. As shown in Figure 4(a), the 48-GHz-band two-tone signal was successfully generated. In this case, not only the noise floor at around 40 dBm but also some undesired frequency components were observed due to the ASE noise and the nonlinear characteristics of optical modulator, respectively. It can be seen from Figure 4(b) that the FWCS effectively eliminated the undesired noise and frequency components. Figure 4(c) shows the received FM-CW RoF signal put into the PD. Also in this case, an undesired component was observed due to a leakage of the OOK uplink signal from the port #1 of OC. It is expected that the undesired component is not seriously affect the generation of desired 48-GHz-band FM-CW signal because it will still appear out of band. Figures 4(d) and (e) show the output of the first SFP+ and the input to the FWCS for the uplink. Figure 4(f) shows the received OOK signal put into the second SFP+. As can be seen, two undesired components, whose level was about 32-dB lower than that of desired OOK signal, were observed due to a leakage of the FM-CW RoF downlink signal from the port #1 of FWCS. Because the input level difference of the downlink and uplink signals was about 8 dB, it is also considered from Figure 3(f) that the leakage level of −32 dB is adequate. Here, it is also expected that the leakage is enough small not to seriously affect the BER. For a 96-band FM-CW RoF signal for the downlink and a 10-Gb/s optical OOK signal for the uplink, it is confirmed that the de-multiplexing performance of FWCS was similar to that in Figure 4.

To verify the FM-CW signal generation via the optical full-duplex link for the downlink, we measured the spectrogram. The measured spectrograms are shown in Figures 5(a) and (b). As mentioned above, the 96-GHz-band FM-CW signal was measured after down-converted to 11-GHz-band FM-CW signal. It can be seen from Figure 5(a) that the frequency sweeping of 8 GHz from 7 to 15 GHz was successfully obtained with the repetition time of 10 µsec. Since the spectrogram for 48-GHz-band FM-CW signal was directly measured, the frequency sweeping of 4 GHz from 46 to 50 GHz was also successfully obtained with the same repetition time of 10 µsec. From the results, it can be verified that the leakage of OOK uplink signal did not seriously affected the FM-CW signal generation as expected.

To evaluate the transmission quality for the uplink, we also measured the BER at the output of the second SFP+. The measured BERs are shown in Figure 5(c), where the circle, the diamond, and square marks represent the BERs without any FM-CW signal, with the 96-GHz-band FM-CW signal, and with the 48-GHz-band FM-CW signal, respectively. Here, it is noted that the

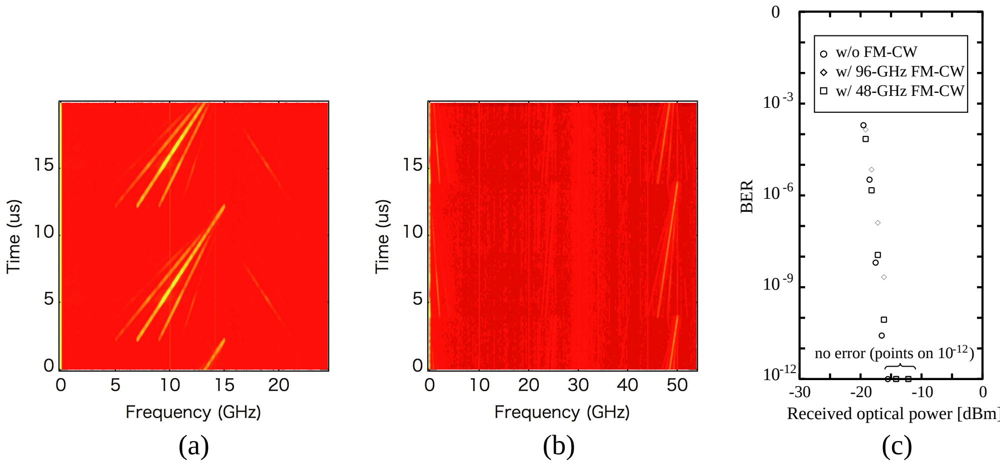

Figure 5: Measured spectrograms at the output of PD: (a) 96-GHz-band FM-CW signal, which was measured in the intermediate-frequency range, and (b) for 48-GHz-band FM-CW signal, and (c) measured BERs.

points on the BER of 10^{-12} represent that no error was observed within the measuring time at the measured received optical power. From Figure 5(c), the BER of less than 10^{-12} was achieved for all the cases. Compared with the BER with no FM-CW signal, no serious BER degradation was observed when the FM-CW downlink signal was transmitted as expected. From the above, it can be concluded that our proposed optical frequency-interleaving full-duplex technique is useful for a fiber-optic simultaneous transmission of a mm-wave-band FM-CW RoF signal for the downlink and a 10-Gb/s-class optical OOK signal for the uplink.

4. CONCLUSION

We have proposed the optical frequency-interleaving full-duplex technique for a fiber-optic simultaneous transmission of a mm-wave-band FM-CW RoF signal for the downlink and a 10-Gb/s-class optical OOK signal for the uplink. We also experimentally demonstrated that no serious degradation for both the downlink and the uplink transmission was observed even if our proposed full-duplex technique was introduced in the fiber-optic full-duplex link.

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