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A Full-duplex WDM Millimeter-Wave-Band Radio-on-Fiber System Using A Supercontinuum Light Source

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***Abstract* — We demonstrate a full-duplex WDM millimeter-wave-band radio-on-fiber (RoF) system using a supercontinuum (SC) light source. For downlink transmission, the periodic nature of arrayed waveguide grating, where the period is free spectral range, is used for utilizing the full bandwidth of the SC light source. Half of the SC output modes are used for uplink transmission with photonic downconversion. These techniques are effective to use a wealth of optical frequency resources from the SC light source. Two-channel downlink and one-channel uplink 60-GHz band RoF signals were simultaneously transmitted over 25-km standard single-mode fiber with error-free and no noticeable power penalty.**

***Index Terms* — Radio-on-fiber (RoF), supercontinuum (SC) light source, wavelength division multiplexing (WDM), photonic up- and downconversion, arrayed waveguide grating, millimeter-wave radio communication, optical waveguide filters**

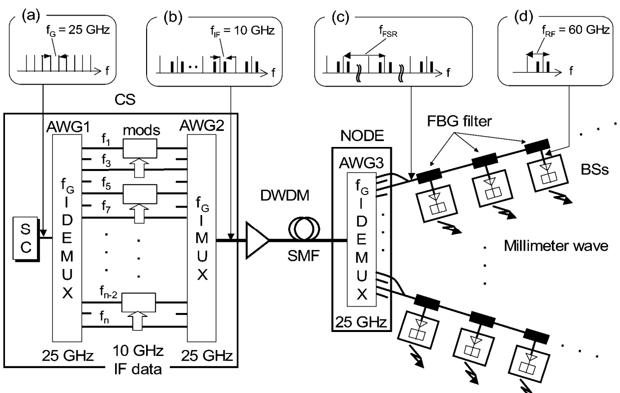
I. INTRODUCTION

For future millimeter-wave-band (mm-wave-band) radio-on-fiber (RoF) systems, it is important to apply dense wavelength division multiplexing (DWDM) to support a large number of base stations (BSs) connected to a central station (CS) [1-3]. For this purpose, we have proposed to use a supercontinuum (SC) light source [4, 5], where the bandwidth of an optical frequency comb (SC modes) generated by a seed pulsed laser is broadened by means of optical nonlinearity of a properly designed fiber [6]. Arrayed waveguide gratings (AWGs) were used for demultiplexing and multiplexing the SC modes. So far, we have confirmed that the SC light source is a potential light source for WDM mm-wave RoF systems. However, the evaluation was limited to downlink application. In this paper, we propose and demonstrate a full-duplex WDM mm-wave-band RoF system using a SC light source.

II. BUS-LINK CONFIGURATION USING A PERIODIC NATURE OF AWG PLACED AT A NODE

Fig.1 illustrates a downlink configuration of a WDM mm-wave-band RoF system using a single SC light source as the multi-wavelength light source. The SC light source generates a broadband optical frequency comb with the spacing of f_G (= 25 GHz in the figure). Individual SC mode, whose frequency is denoted by f_n (n: integer number), is extracted by a demultiplexer (DEMUX: AWG1). In the figure, we employ the photonic up-conversion technique [4], where the optical modes at f_{4i+1} (i: integer number) are modulated by IF data independently. An f_G-spaced DEMUX (AWG3), where the free spectral range (FSR) is denoted by f_{FSR}, which is a multiple of f_G, is placed at a node. This DEMUX feeds the RoF signals separated by f_{FSR} to each bus link. Each RoF signal can be extracted by a fiber Bragg grating (FBG) filter. By using the periodic nature of the AWG, where the period is FSR, the size of AWG3 can be smaller even when the full bandwidth of the SC light source is used. Also each BS does not need to be connected to the node individually, which greatly saves the total fiber length for the BSs. Note that the periodic nature of AWG1 and AWG2 may be able to be used in the CS in conjunction with FBG filters in order to save the complexity of the AWGs.

In this example, only odd number of the SC modes are used for downlink. This is because 50-GHz spaced SC modes suit well for photonic upconversion to generate 60-GHz RoF signals, while the SC mode spacing is 25 GHz. Therefore, we propose to use the rest of the SC modes for uplink to realize a full-duplex RoF system.



CS: central station, mods: modulators, BS: base station,
AWG: arrayed waveguide grating, FBG: fiber Bragg grating
SC: supercontinuum light source (mode spacing: f_G)

Fig. 1 A downlink configuration of a WDM mm-wave RoF system using a SC light source.

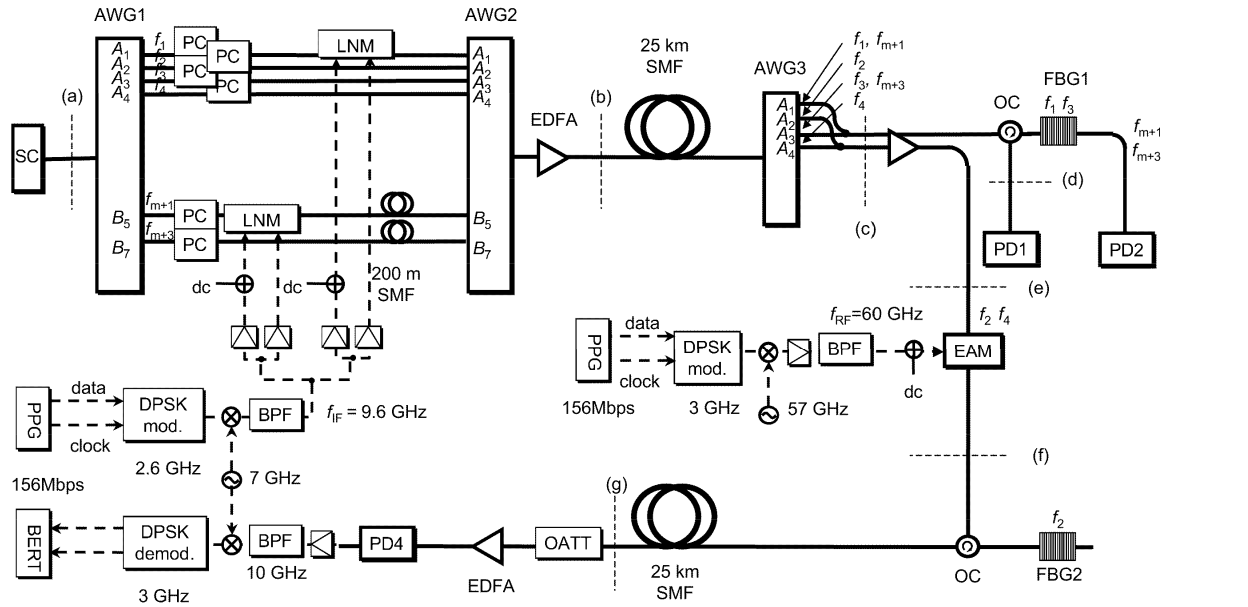


Fig. 2 Experimental setup for the full duplex configuration. In the experiment, two downlink channels and one uplink channel are transmitted simultaneously.

III. Full Duplex Configuration with Photonic Up- and Downconversion

A. Experimental setup and operation principle

Fig. 2 shows the experimental setup for the full duplex configuration. In the experiment, we will show transmission of two downlink channels and one uplink channel simultaneously. Fig. 3 shows conceptional optical spectra of (a); SC outputs, (b); after modulation, (c); AWG 3 output, and (d); PD1 input, respectively. D and U indicate downlink and uplink, respectively. Modulation was performed by 9.6-GHz IF signal carrying a 156 Mbps DPSK data with $LiNbO_3$ Mach-Zehnder modulators (LNMs). The FSR of the AWG3 used in the experiment was f_m = 0.80 THz (= 6.4 nm at 1550 nm). Fig. 4 shows optical spectra for uplink signal. The 50-GHz spaced even number SC modes f_2 and f_4 are filtered by AWG3 (Fig. 4 (e)). The two SC modes are simultaneously intensity modulated with an electro-absorption modulator (EAM) by 60-GHz mm-wave signal carrying 156 Mbps DPSK data (Fig. 4 (f)). Finally the carrier f_2 and single sideband f_2 - f_{IF} is filtered by narrow band FBG2 and photodetected by PD4. Here, photonic downconversion [7] allows us to detect 10-GHz IF signal after photodetection of the 60-GHz RoF signal.

The SC light source used in the experiment is NTT Electronics, NIESP-SC-001, which is driven by a seed mode-locked laser diode with the repetition rate of 25 GHz (= f_G). The SC modes are ranging from 1534 nm to 1599 nm with +/– 5 dB flatness, except for several nanometers around the seed laser wavelength (1565 nm). The output power of the individual SC mode around 1552 nm and the total output power of the SC light source is – 8 dBm and + 22 dBm, respectively. The AWG1 and AWG2 were tuned by temperature to the SC modes. The carrier wavelengths of the downlink channels 1 and 2 are 1546.7 and 1553.1 nm, respectively. The 3-dB bandwidths of FBG1 and FBG2 are 1.4 nm

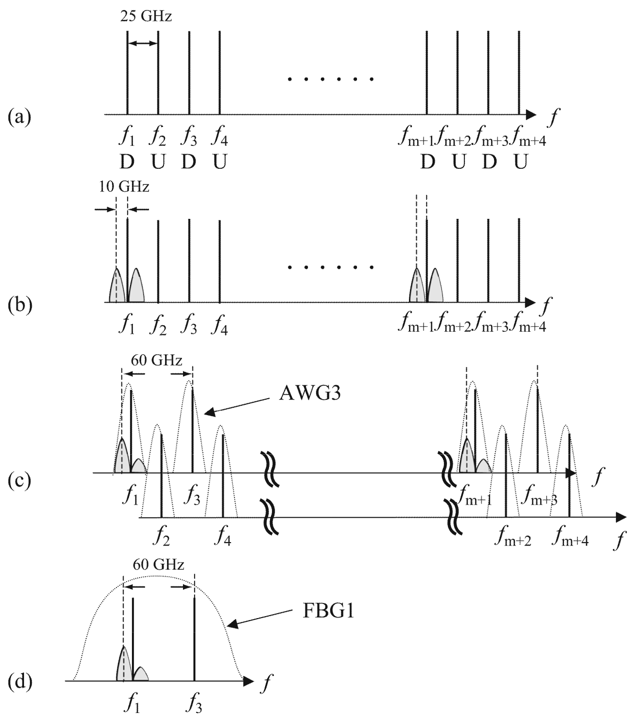


Fig. 3 Conceptional optical spectra of (a); SC outputs, (b); after modulation, (c); AWG 3 output, and (d); PD1 input. D and U indicate downlink and uplink, respectively.

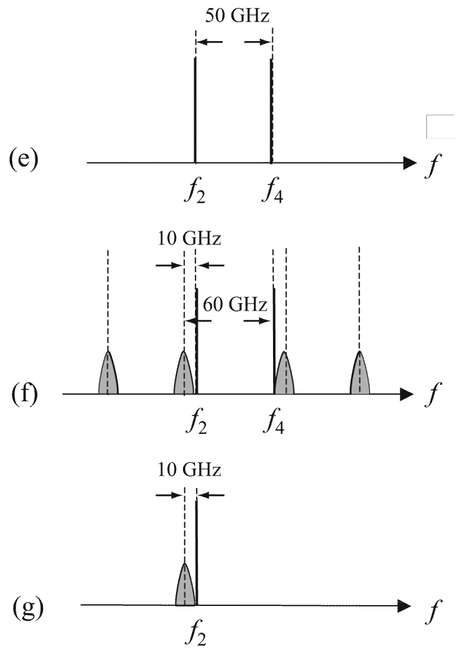


Fig. 4 Optical spectra for uplink signal. (e); 50-GHz spaced two SC modes for the uplink signal (EAM input), (f); after modulation by 60 GHz mm-wave signal (EAM output), and (g); reflection of FBG2 (PD4 input). Photonic downconversion allows us to detect 10-GHz IF signal after photodetection.

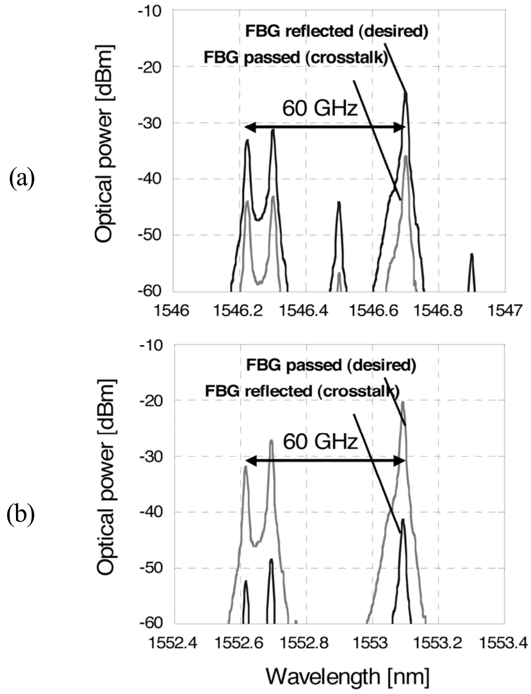


Fig. 5 Measured optical spectra of the two downlink RoF signals at FBG1 outputs: (a) channel1 and (b) channel2.

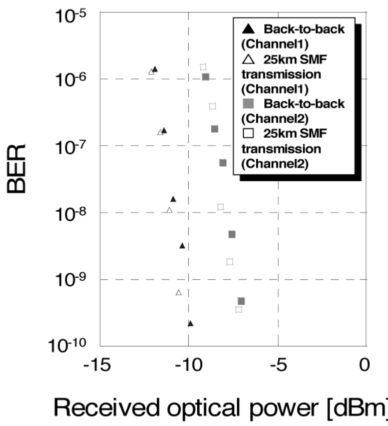


Fig. 6 Measured BERs for downlink RoF signals as a function of received optical power.

and 0.2 nm, respectively. Finally, the bit-error rates (BERs) of the decoded 156-Mbps data for up- and downlink transmission are measured.

B. Downlink results

Here we present the results of downlink transmission. Once again, note that all signals (two downlink and one uplink) are transmitted simultaneously during the experiment in order to clarify full-duplex operation. Fig. 5 shows the measured optical spectra of the two RoF signals (channels 1 and 2) detected at the FBG1 outputs. Separation between the carrier and the desired sideband is 60 GHz as indicated by arrows. From these spectra, one can estimate the mm-wave signal level of the undesired channel to be suppressed by about - 35 dB and - 28 dB of the desired signal level for channels 1 and 2.

We measured the BERs of channels 1 and 2 versus the received optical power. Fig. 6 plots the results. As shown in the figure, the error-free transmission (BER < 10^{-9}) for both channels are simultaneously achieved. The difference in the optical receiver sensitivity may be attributed to the difference of carrier to sideband ratio (CSR). Here, CSR means the power difference between the optical carrier and the 60 GHz sideband. The power penalty of less than 0.5 dB was observed after 25-km SMF transmission. This is because that the undesired sideband of the RoF signal is effectively suppressed by the AWG. Therefore, the RoF signal is free from the signal fading problem due to the chromatic dispersion of the transmission fiber.

B. Uplink results

Fig. 7 shows optical spectra, which corresponds to (e), (f) and (g) of Fig. 4. Even though the considerable amount of crosstalk can be seen in the figure due to the crosstalk of the AWGs, One can see that this crosstalk does not influence so much on the receiver performance since the beat signals due to the crosstalk is out of 10 GHz band. Fig. 8 shows measured BER versus received optical power, which is defined as the optical input

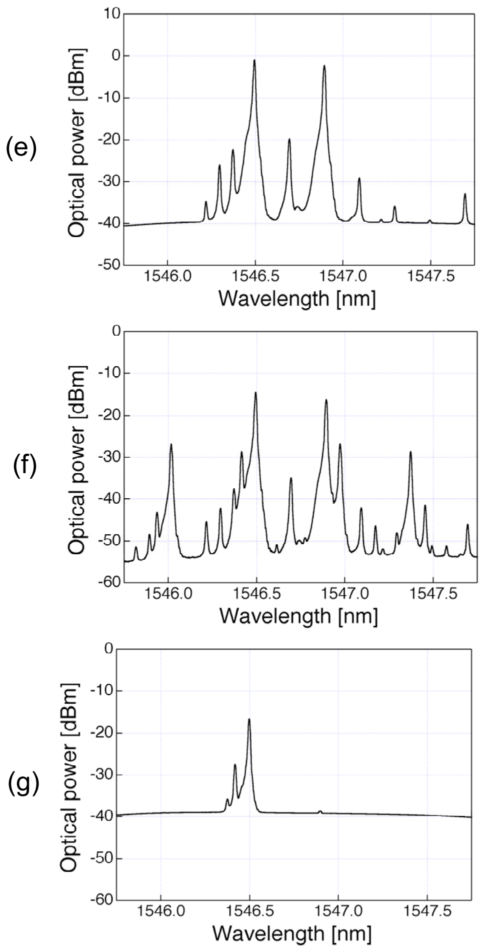


Fig. 7 Measured optical spectra of the uplink RoF signal which corresponds to (e), (f) and (g) of Fig. 4.

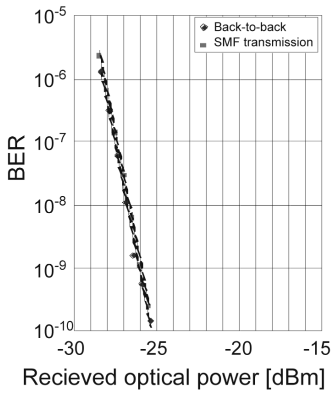


Fig. 8 Measured BERs for the uplink RoF signal as a function of received optical power.

power of pre-EDFA for PD4 in Fig. 2. As shown in Fig. 2, we used an EDFA in front of EAM because the optical power to the pre-EDFA was slightly less than the power needed for error-free operation. Since one does not want to put an EDFA at this position, we should analyze power diagram of the system to remove this EDFA in future. Nevertheless, error free transmission was obtained as seen in the figure. No noticeable power penalty was observed after 25-km SMF transmission. This is once again because that the undesired sideband component of the RoF signal is effectively suppressed by AWGs and FBG2.

IV. Conclusion

We proposed and demonstrated a full-duplex WDM millimeter-wave-band RoF system using a SC light source. For downlink transmission, the periodic nature of AWG, where the period is FSR, was used for utilizing the full bandwidth of the SC light source. Half of the SC output modes were used for uplink transmission with photonic downconversion. These techniques are effective to use a wealth of optical frequency resources from the SC light source. Two channel downlink and one-channel uplink 60-GHz band RoF signals were simultaneously transmitted over 25-km standard single-mode fiber with error-free and no noticeable power penalty. Feature works include multi-channel full duplex transmission of WDM RoF signals.

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