5-2 High-Spectral Density Multiplexing Transmission and Photonic Mixing for Millimeter-Wave-Band Radio-on-Fiber Systems

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Two system architectures based on dense wavelength division multiplexing (DWDM) for millimeter-wave-band (mm-wave-band) radio-on-fiber (ROF) systems are described. One architecture consists of a wavelength multiplexer and demultiplexer with arrayed waveguide gratings (AWGs) for optical-frequency-interleaved DWDM ROF transmission. The other architecture is based on a photonic down-conversion technique that is used in DWDM ROF systems. A 25-GHz-spaced, 60-GHz-band DWDM ROF transmission with photonic down-conversion is experimentally demonstrated.

Keywords
Dense wavelength division multiplexing, Millimeter-wave, Radio-on-fiber, Fiber dispersion, Photonic down-conversion

1 Introduction

Millimeter-wave-band (mm-wave-band) radio-on-fiber (ROF) systems will have smaller cells than those of microwave-band ROF systems, because the frequency of mm-wave-band radio is higher than that of microwave-band radio. However, mm-wave-band ROF systems must still meet certain practical requirements: they need to provide wide service coverage and have a large capacity, and the system configuration needs to be cost-effective. Consequently, it is important to achieve an effective transmission of mm-wave-band ROF signals from a central station (CS) to a large number of base stations (BSs), and vice versa. A simple approach for connecting all BSs in future fiber-optic access networks is dense wavelength division multiplexing (DWDM).

There have been several reports on DWDM ROF systems for effective use of single optical fiber [1]-[4]. To increase the optical-spectral efficiency, an optical frequency interleaving technique has been proposed [5], whose wavelength multiplexer and demultiplexer are based on fiber Bragg gratings (FBGs). Moreover, the author has proposed a photonic down-conversion technique with optical frequency shift, which can be effectively incorporated into mm-wave-band ROF systems [6].

In this paper, two system architectures based on DWDM for mm-wave-band ROF systems are described. One architecture consists of a wavelength multiplexer and demultiplexer with arrayed waveguide gratings (AWGs) for optical-frequency-interleaved DWDM ROF transmission [7][8]. The other architecture is based on a photonic down-conversion technique that is used in DWDM ROF systems [9]. A 25-GHz-spaced, 60-GHz-band 2-channel-DWDM ROF transmission with photonic down-conversion is experimentally demonstrated.

2 DWDM ROF System Architectures

From the viewpoint of reducing system cost, it is preferable to use the DWDM channel allocation in accordance with the International Telecommunication Union (ITU) grid. To avoid inter-channel interference in 60-GHz-band ROF systems, the minimum channel spacing is 200 and 100 GHz for optical double sideband (DSB) and optical single sideband (SSB) formats, respectively. In these cases, the optical-frequency resource cannot be fully utilized. However, this problem can be easily overcome by interleaving the optical frequency. In the case of 25-GHz spacing with the optical SSB format, for example, the optical-spectral efficiency can be increased by

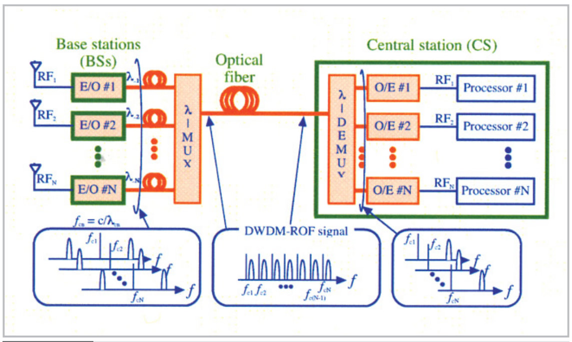

Fig. 1 System architecture I

four times. In theory, the optical-spectral efficiency could be further improved by closing up the channel spacing. However, if this is done, we must ensure that one channel does not interfere with the other channels. In the rest of paper, the discussions are concentrated on 25-GHz-spacing optical-frequency-interleaved DWDM ROF systems because optical devices for 25-GHz-spacing DWDM baseband transmission are the most practical targets at present.

2.1 System Architecture I

Figure 1 shows the conceptual system architecture of an optical-frequency-interleaved DWDM ROF system with a star topology (system architecture I), where it is assumed to be an uplink system. The uplink ROF signals generated from each BS are multiplexed at a DWDM ROF multiplexer (λ-MUX) and transmitted over a single optical fiber to the remote CS. Here, a wavelength (λ_n, $n = 1, 2, \cdots N$) that is in accordance with the ITU grid is individually allocated to BS_n. The optical-frequency-interleaved DWDM ROF signal received at the CS is demultiplexed by a DWDM ROF demultiplexer (λ-DEMUX), put into an individual optical-to-electrical (O/E) converter, and demodulated with a radio-frequency (RF)-band processor. It is shown below how the multiplexed and demultiplexing of optical-frequency-interleaved DWDM ROF signal can be achieved.

Figure 2 shows the λ-MUX scheme for an optical-frequency-interleaved DWDM ROF signal [7]. There are two viable configurations of λ-MUX, which have almost the same function as a multiplexer. One λ-MUX consists of

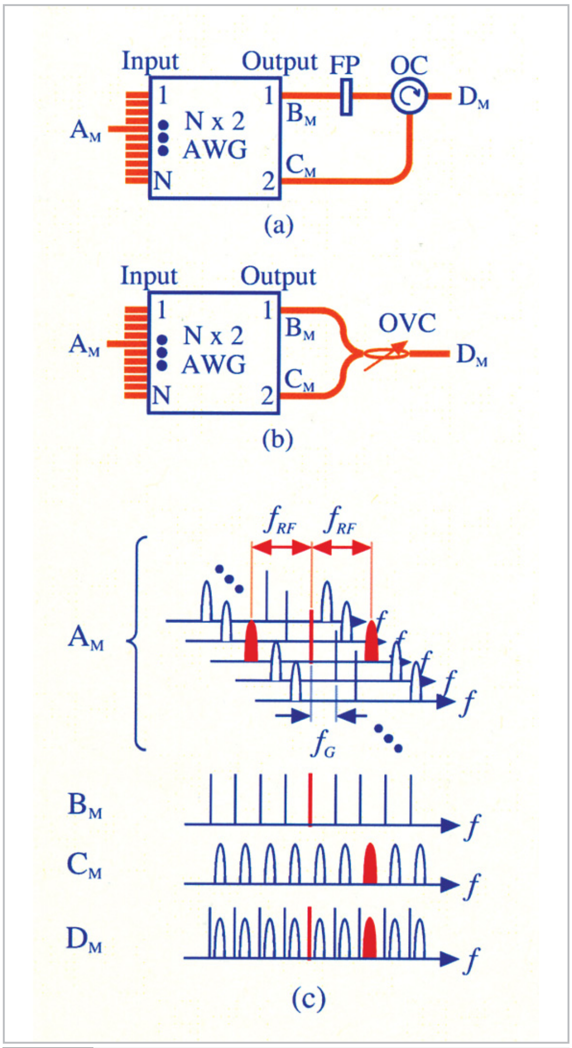

Fig. 2 λ-MUX

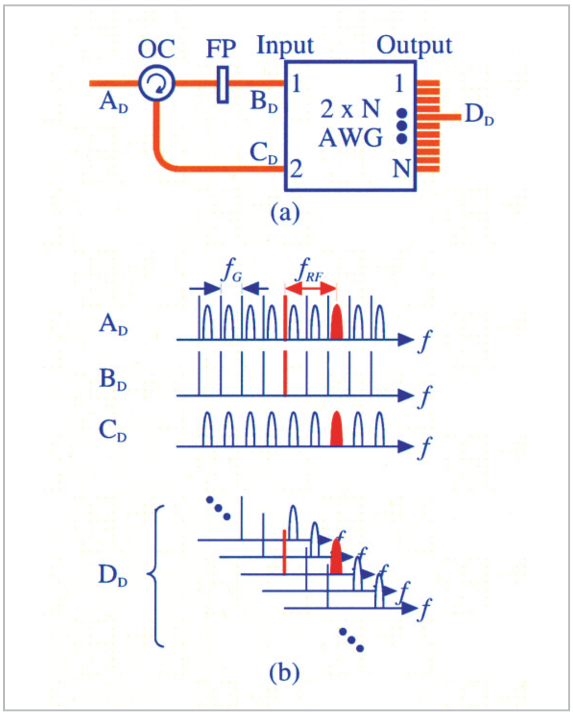

Fig.3 λ-DEMUX

an $N\times2$-AWG, a high-finesse Fabry-Perot (FP) filter, and an optical circulator (OC), as shown in Fig.2 (a). The other λ-MUX consists of the same AWG and an optical variable coupler (OVC), as shown in Fig.2 (b). Many ROF signals that have carriers allocated according to the ITU grid for each BS are input to each port of the AWG, as shown in Fig.2 (c). The AWG extracts the carrier component B_M and one of the sideband components C_M of the input channel A_M. Then, the AWG guides them to the distinct output ports. The extracted carrier B_M and sideband C_M are combined with the OVC to make the desired DWDM ROF signal D_M, which is optical-frequency interleaved. Compared the input A_M with the output D_M, this scheme operates the optical-frequency-interleaving DWDM multiplexer as well as the optical SSB filtering for all ROF channels. In addition, the OVC of the λ-MUX shown in Fig.2 (b) can simultaneously control the modulation index of all ROF channels by changing the coupling ratio.

Figure 3 shows the λ-DEMUX scheme for an optical-frequency-interleaved DWDM ROF signal [8]. As shown in Fig. 3 (a), the λ-DEMUX consists of a high-finesse FP filter, an OC, and a $2\times N$-AWG, where the difference from the λ-DEMUX shown in Fig.2 (a) is only the direction of the OC. f_G and f_{RF} are the DWDM channel spacing and the RF carrier frequency, respectively. Each ROF signal is assumed to have an optical SSB format, as shown in A_D of Fig.3 (b). For the signal A_D, the FP separates the carriers B_D from the sidebands C_D. The AWG then guides the desired pair of carrier and sideband components to the same output port, as shown in D_D. The optical-frequency-interleaved DWDM ROF signal is thus demultiplexed.

2.2 System Architecture II

Figure 4 shows the conceptual system architecture of a DWDM ROF system with the photonic down-conversion (system architecture II) [9]. The photonic down-conversion is difined as a function of the conversion from the RF band to intermediate-frequency (IF)-band through an optical link. It is assumed that the DWDM ROF signal is optical-frequency interleaved. The received signal is optically pre-processed at the front-end of the CS and then demultiplexed by λ-DEMUX. Each demultiplexed signal is photonic-down-converted signal via the O/E converter, and demodulated with the IF-band processor. According to this architecture, all multiplexed ROF signals are subjected to the photonic down-conversion process simultaneously. Furthermore, this architecture does not require high-frequency components on the receiver side. Therefore, even though the number of multiplexed channels increases, the system cost does not increase much .

Figure 5 shows the optical spectrum allo-

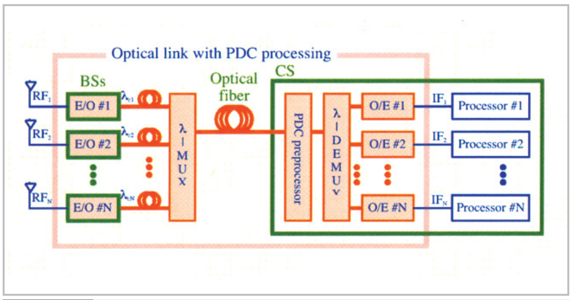

Fig.4 System architecture II

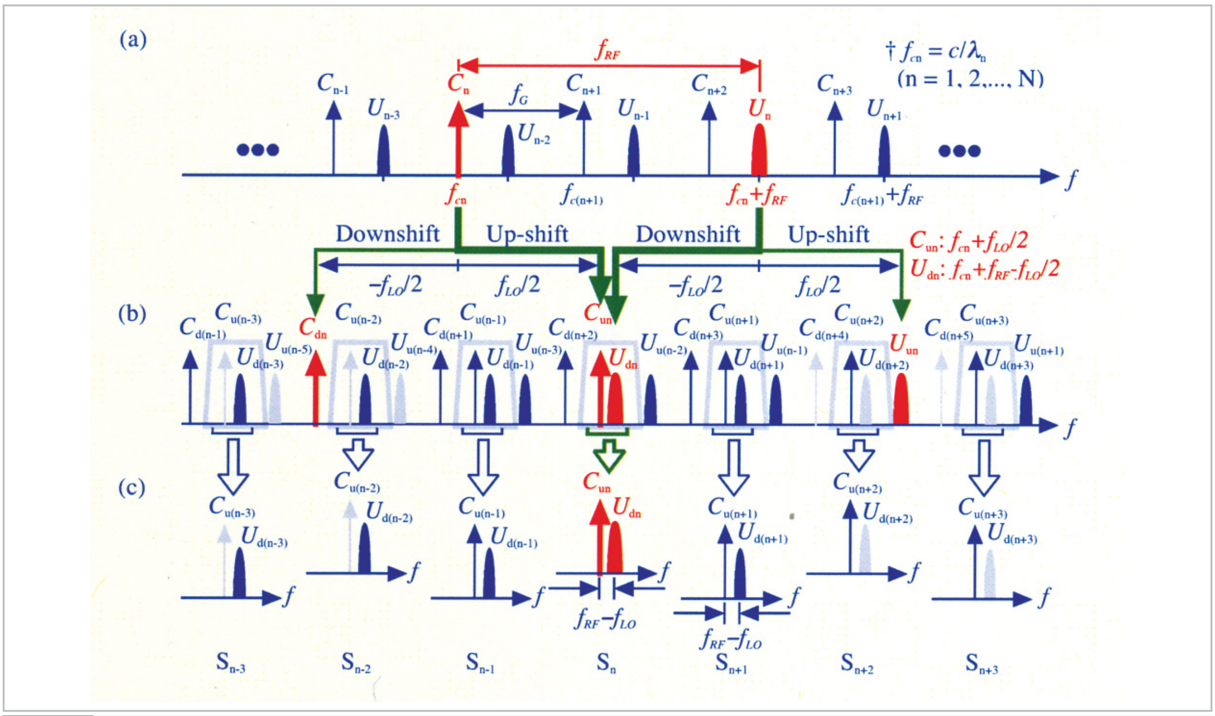

Fig.5 Spectrum design.(a)DWDM ROF signals,(b)frequency-shifted DWDM ROF signals,and (c)demultiplexed optical channels.

cation of the DWDM ROF channels with the photonic down-conversion. In Fig.5 (a), C_n and U_n represent the carrier and the upper sideband (USB) of n-th channel from BS_n, respectively, where each ROF signal is assumed to have an optical SSB format to avoid the fiber dispersion effect. f_{cn} [= c/ λ_{cn}] and f_{RF} represent the optical carrier frequency of the n-th channel and the RF carrier frequency, respectively. The optical carriers are assumed to be in accordance with the ITU grid, where the spacing is f_G [= $f_{c(n+1)}$-f_{cn}]. In the photonic down-conversion, a group of the multiplexed ROF signals is first equally power-split and frequency-shifted by -f_{LO}/2 and f_{LO}/2. In the frequency-shifted DWDM signals shown in Fig.5 (b), C_{dn}, C_{un}, U_{dn}, and U_{un} are the down-shifted carrier, the up-shifted carrier, the down-shifted first-order USB, and the up-shifted first-order USB of the n-th channel, respectively. Through the frequency shift, the carrier (C_n) and USB (U_n) in a mm-wave-band ROF signal are differentially shifted closer to each other. Next, each pair of the closely aligned components, S_n, which consists of C_{un} and U_{dn}, is filtered out with the λ-DEMUX, as shown in Fig.5 (c). After that, each optical signal S_n is photodetected to generate the desired IF-band signal in the microwave band (f_{IF} [= f_{RF} -f_{LO}]). Thus, the photonic down-conversion can be performed in optical-frequency-interleaved DWDM ROF systems.

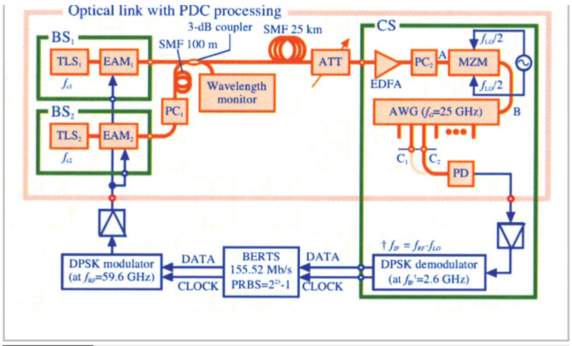

Fig.6 Experimental setup

3 Experimental Results

Figure 6 shows the experimental setup to verify the photonic down-conversion function for use in optical-frequency-interleaved DWDM ROF systems. The setup mainly consists of two simple BSs, a 25-km-long standard single-mode optical fiber (SMF), and one

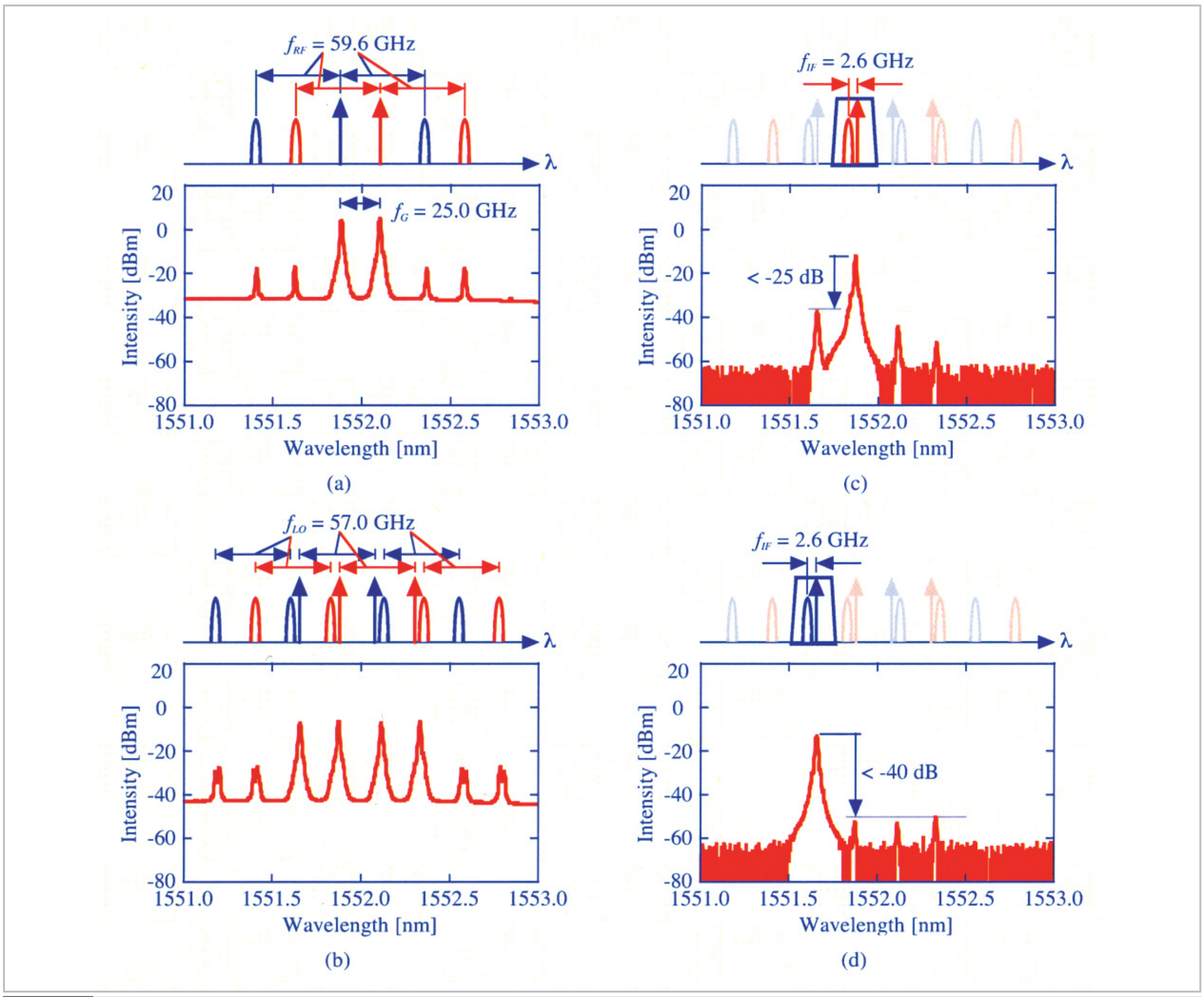

Fig.7 *(a)Pre-processor input,(b)pre-processor output,(c)selected ch.1,and (d)selected ch.2.*

CS. Each ROF signal was made with a 59.6-GHz carrier, which carries 155.52-Mb/s differential-phase-shift-keying (DPSK) data. A 100-m-long fiber was used to reduce the correlation between two channels. The CS mainly consists of a dual-electrode Mach-Zehnder modulator (MZM) for optical frequency shifting, an AWG for demultiplexing, and a photodetector as an O/E converter. The driving condition of the MZM was set to work as a carrier-suppressed double sideband (DSB-SC) modulator.

The measured optical spectra are shown in Fig.7. The two 60-GHz-band ROF signals were separated by 25 GHz as shown in Fig.7 (a). As such, they were also optically frequency-interleaved. The carrier linewidths at 1551.9 and 1552.1 nm were 300 kHz. Note that each ROF signal after multiplexing had the optical DSB format because an optical 3-dB coupler was used as a λ-MUX for simplicity of the setup. From Fig.7 (b), it can be seen that each optical component was successfully down- and up-shifted in the optical domain. Since the input to the DSB-SC modulator was 28.5-GHz local tone, the total separation of each optical component was 57.0 GHz. Figures 7 (c) and (d) show the AWG output for chs. 1 and 2. Two pairs of optical components (at around 1551.9 and 1551.7 nm) were successfully filtered out with a suppression ratio of less than -25 and -40 dB for chs. 1 and 2, respectively. As shown in the description spectra drawn on their measured spectra, the extracted signal has two components: a carrier and a sideband. The sideband component is separated by 2.6 GHz [= 59.6-57.0 GHz] from the carrier for both channels. Here, note again

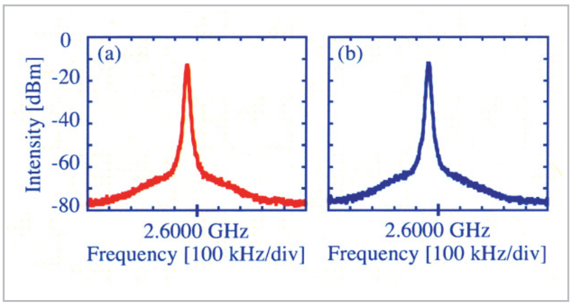

Fig.8 Photodetected signals without data for (a)ch.1 and (b)ch.2.

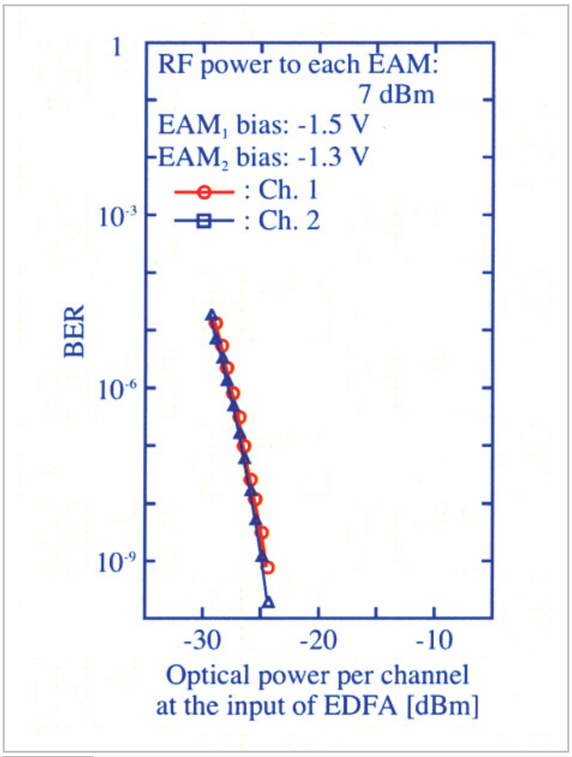

Fig.9 Measured BERs

that the optical DSB format (the original ROF signal) is converted to the optical SSB format (the closely aligned ROF signal) through the photonic down-conversion process. This refers to the tolerance of the system performance to fiber dispersion.

The electrical spectra after photodetection were measured without payload data to clearly show the frequency conversion. The results are shown in Fig.8. These figures show that the photodetected signals occurred in the microwave band as expected, and their central frequency was 2.6 GHz with a very narrow spectrum linewidth. This result suggests that the original RF-band signal at 59.6 GHz was successfully downconverted to the desired IF-band signal at 2.6 GHz through the optical link simultaneously for both channels.

The transmission quality of the optical-frequency-interleaved DWDM ROF system with the photonic down-conversion technique was also investigated. Figure 9 shows the measured bit error rates (BERs) after 25-km SMF transmission. It was an error-free transmission, that is, all channels achieved a BER of less than 10^{-9}. Moreover, no BER floor appeared within the measured optical power range. This result shows that the crosstalk of 25 and 40 dB is negligible when the BER is 10^{-9}. Therefore, we concluded from these results that the presented photonic down-conversion technique can be applied to future DWDM ROF access networks.

4 Conclusion

Two system architectures for mm-wave-band DWDM ROF systems were developed. In the first architecture, the optical-frequency-interleaved DWDM ROF signal was transmitted with a λ-MUX and λ-DEMUX, which were configured with AWGs. In the second architecture, the photonic down-conversion technique was extended for use in optical-frequency-interleaved DWDM ROF systems to achieve a cost-effective system configuration. The photonic down-conversion technique applied to a 25-GHz-spacing 2-channel-DWDM ROF signal was experimentally verified; a 25-km SMF transmission was successfully demonstrated. We concluded that our photonic down-conversion technique could be practically applied to future DWDM ROF access networks.

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References

1 K. Kitayama, "Highly spectrum efficient OFDM/PDM wireless networks by using optical SSB modulation," IEEE/OSA J. Lightwave Technol., vol. 16, no. 6, pp. 969-976, June 1998.

2 K. Kitayama, T. Kuri, K. Onohara, T. Kamisaka, and K. Murashima, "Dispersion effects of FBG and optical SSB filtering in DWDM millimeter-wave fiber-radio systems," IEEE/OSA J. Lightwave Technol., vol. 20, no. 8, pp. 1397-1407, Aug. 2002.

3 K. Kojucharow, M. Sauer, H. Kaluzni, D. Sommer, C. Schaffer, "Experimental investigation of WDM channel spacing in simultaneous upconversion millimeter-wave fiber transmission system at 60 GHz-band," in IMS2000 Tech. Dig., vol. 2, WE4C-7, 2000, pp. 1011-1014.

4 A. Narasimha, X. J. Meng, M. C. Wu, and E. Yablonovitch, "Tandem single sideband modulation scheme for doubling spectral efficiency of analogue fibre links," Electron. Lett., vol. 36, no. 13, p. 1135-1136, June 2000.

5 C. Lim, A. Nirmalathas, D. Novak, R. S. Tucker, and R. B. Waterhouse, "Technique for increasing optical spectral efficiency in millimetre-wave WDM fibre-radio," Electron. Lett., vol. 37, no. 16, pp. 1043-1045, Aug. 2001.

6 T. Kuri, and K. Kitayama, "Novel photonic down-conversion technique with optical frequency shifter for millimeter-wave-band radio-on-fiber systems," IEEE Photon. Technol. Lett., vol. 14, no. 8, pp. 1163-1165, Aug. 2002.

7 H. Toda, T. Yamashita, T. Kuri, and K. Kitayama, "25-GHz channel spacing DWDM multiplexing using an arrayed waveguide grating for 60-GHz band radio-on-fiber systems," in Proc. International Topical Meeting on Microwave Photonics (MWP2003), Budapest, Hungary, pp. 287-290, September 10 -12, 2003.

8 H. Toda, T. Yamashita, T. Kuri, and K. Kitayama, "Demultiplexing using an arrayed-waveguide grating for frequency-interleaved DWDM millimeter-wave radio-on-fiber systems," IEEE/OSA J. Lightwave Technol., vol. 21, no. 8, pp. 1735-1741, Aug. 2003.

9 T. Kuri, H. Toda and K. Kitayama, "Dense wavelength division multiplexing millimeter-wave-band radio-on-fiber signal transmission with photonic down-conversion," IEEE/OSA J. Lightwave Technol., vol. 21, no. 6, pp. 1510-1517, June 2003.

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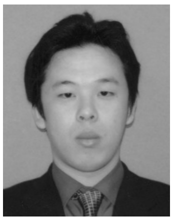

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