2-5 Dense Multiplexing and Transmission Technique of Millimeter-Wave-Band Radio-on-Fiber Signals

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Optical-frequency-interleaved dense wavelength division multiplexing (DWDM) transmission of millimeter-wave-band subcarrier-multiplexed (SCM) radio-on-fiber (RoF) signals with a photonic downconversion technique is described. The photonic downconversion technique is carried out for a lump of all multiplexed RoF signals at the receiver side. Error-free 25-GHz-spacing DWDM transmission and demultiplexing of two 60-GHz-band SCM RoF signals carrying 155-Mb/s differential phase-shift-keying data over 25-km-long standard single-mode fiber are experimentally demonstrated without serious fiber dispersion effect.

Keywords
Radio on fiber (RoF), Wavelength division multiplexing (WDM),
Subcarrier multiplexing (SCM), Millimeter-wave, Photonic downconversion

1 Introduction

Wireless access with radio wave shows exponential increase of demand and will be surely taking an important role in ubiquitous networks in future. A rapid spread of commercial broadband wire lines, such as digital subscriber lines (DSL) and fiber-to-the-home (FTTH) are providing broadband access environment in home as well as office. Such broadband access environment is strongly demanded also in wireless access, which improves convenience in using networks. For future broadband wireless access, high-frequency radio resources, such as millimeter wave and terahertz wave, are being developed, where they have 10 to 1,000 times transmission capacity in comparison with that of existing microwave. However, it has a limit to the transmission distance due to the free-space propagation loss depending on the carrier frequency. While it has the attractive ability of high-speed large-capacity transmission, there is a problem that broadband wireless access service offers only in limited areas.

Radio wave environment turns worse as increasing the kind of radio terminals and growing in their number due to the interference to each other. If increase of emission power or a multi-hop by radio itself is performed to extend the service areas, they become a cause to boost the radio interference. As shown in the left part of Fig. 1, future radio wave environment is becoming more complicated. Under the environment where radio floods in livelihood space, socially serious problems, such as influence to electronics and medical equipments due to jamming and the leakage of radio signals, are expected. Therefore, it is necessary to take safety measures immediately.

Radio-on-fiber (RoF) is a promising technology as one of the core technology to support future ubiquitous networks by cooperating with the fiber-optic access networks, like FTTH, and can systematically connect various radio communication systems. RoF, whose the greatest characteristic is “preservation of radio

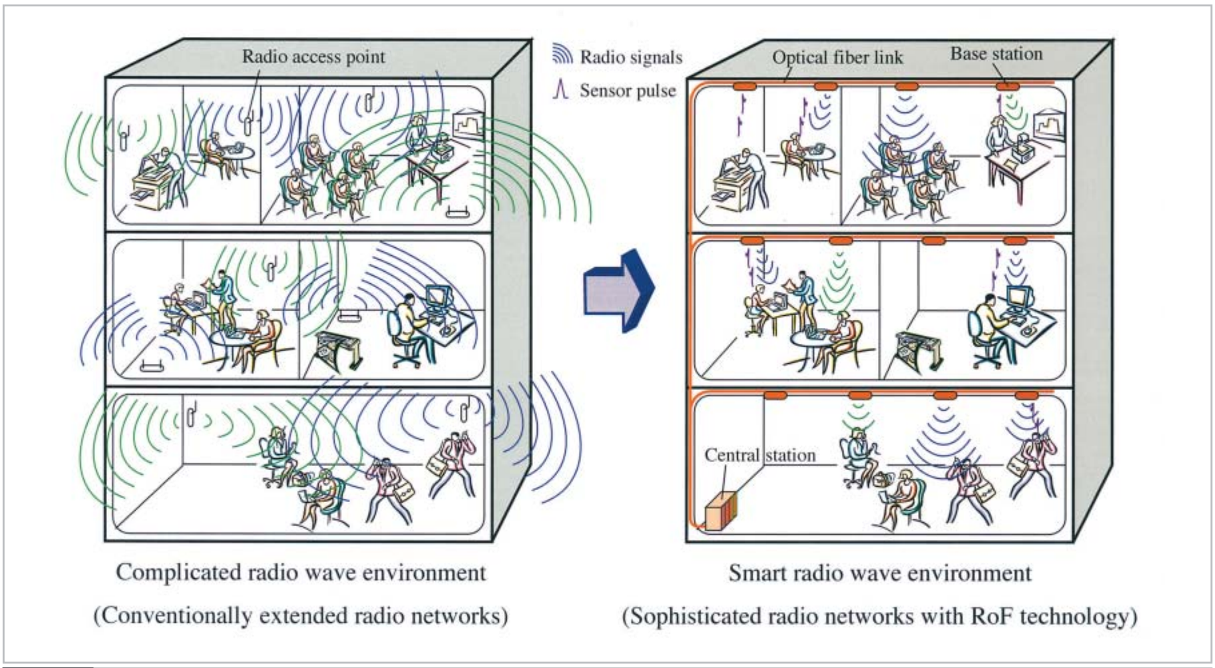

Fig.1 *Radio wave environment*

signal format" and "electromagnetic immunity from radio systems", is one of advanced photonics technologies, and can deliver only the desired radio signal to the place where it is necessary, regardless the frequency band and the transmission bandwidth of radio signal itself. In other words, RoF technology creates the virtual radio space in optical fibers, that is, the situation that whole radio is cooped by photonics technology, and can offer "smart radio wave environment", which means the minimum emission of radio signals to the air without any serious intra-and inter-system interferences as shown in the right part of Fig. 1. Moreover, the RoF technology enables to provide seamless connections among various kind of wireless systems which are remotely located each other, such as wireless local area networks (LANs) and sensor networks.

Under the above situation, various millimeter-wave-band (mm-wave-band) RoF systems have been studied. In future mm-wave-band RoF access networks, highly dense fiber-optic transmission of radio signals will be strongly required not only to deal with a large number of wireless terminals at a central station (CS) but also to effectively use fiber-optic resources[1]-[4]. To effectively increase the channel capacity in existing optical fibers, dense wavelength division multiplexing (DWDM) as well as subcarrier multiplexing (SCM) is a very attractive and useful multiplexing technique. On the other hand, we have proposed the photonic downconversion technique with optical-frequency shift[5][6]. The photonic downconversion technique, which is defined as the frequency conversion function from radio-frequency (RF) band to intermediate-frequency (IF) band via an optical link, brings many merits for mm-wave-band RoF systems; high tolerance of fiber-dispersion effect, high optical receiver sensitivity, and no need of mm-wave-band components. It also leads to the better system performance as well as lower system cost.

In this paper, the photonic downconversion technique adopted to optical-frequency-interleaved DWDM transmission of mm-wave-band SCM RoF signals is described. In the demonstration, 2-channel-DWDM / 2-channel-SCM RoF signals are transmitted over 25-km-long standard single-mode optical fiber (SMF). The multiplexed signal consists of independent four 60-GHz-band RoF signals carrying 155.52-Mb/s differential phase-shift-keying (DPSK) data.

2 Principle

Figure 2 shows the general architecture of an optical-frequency-interleaved DWDM / SCM RoF system with a star topology. In each antenna base station (BS), several received radio signals are bundled together in a group as an SCM-RF signal, and the SCM-RF signal then modulates an optical carrier to generate an SCM-RoF signal via electrical-to-optical (E/O) convertor. The SCM-RoF signals from BSs at different wavelengths are multiplexed at a wavelength multiplexer (λ-MUX) in a remote node and transmitted over a fiber-optic link to the CS. The DWDM / SCM-RoF signal received at the CS is at first frequency-shifted in the optical domain, and then demultiplexed by a wavelength demultiplexer (λ-DEMUX). The outputs put into an individual optical-to-electrical (O/E) converter to generate the SCM-IF signals. Then, each regenerated SCM-IF signal is demultiplexed and individually demodulated. Here, the key is the optical frequency shift before O/E conversion. The frequency shift by a predicted frequency leads to the desired photonic downconversion. According to this architecture, all multiplexed RoF signals are subjected to photonic downconversion process simultaneously. Also, this architecture doesn't require having high-frequency components on the receiver side, that is, the CS side. Therefore, even though the number of multiplexed channels increases, the system cost doesn't increase so much and the cost per channel decreases.

In the above system concept, an important point is how to successfully apply the photonic downconversion technique to DWDM / SCM-RoF signals. Figure 3 shows one example of the spectrum design in an optical-frequency-interleaved DWDM / SCM RoF system. C_n, $L_{(n, m)}$, and $U_{(n, m)}$ are the carrier component of n-th DWDM channel (n = 1, 2, ..., N), the lower sideband (LSB) and the upper sideband (USB) of the m-th SCM channel (m = 1, 2, ..., M) on the n-th DWDM channel (called (n, m)-th Channel below), respectively. f_{cn}, f_{RFm}, and f_G [= $f_{c(n+1)} - f_{cn}$, (n = 1, 2, ..., N−1)] are the optical carrier frequency of the n-th DWDM channel, the mm-wave-band carrier frequency of the m-th SCM channel, and the minimum frequency interval between two DWDM channels, where the frequency interval of DWDM channels is assumed to be equally spaced. It is assumed that the multiplexed RoF signals shown in Fig. 3(a) are received at CS. Each optical carrier is modulated by an SCM RF signal generated in electrical domain. To effectively use the optical frequency resource, f_G is set to be less than f_{RFm} and DWDM RoF channels are interleaved each other as shown in Fig. 3(a). A lump of the DWDM / SCM RoF signal is equally power-split and frequency-shifted by $-f_{LO}/2$ and $f_{LO}/2$. Figure 3(b) shows the multiplexed signal after the frequency shift. Here, f_{LO} should be carefully set not to overlap each other. By the optical frequency shift, the carrier (C_n) and one of the first-order sideband components ($U_{(n, m)}$ (m = 1, 2, ..., M), for

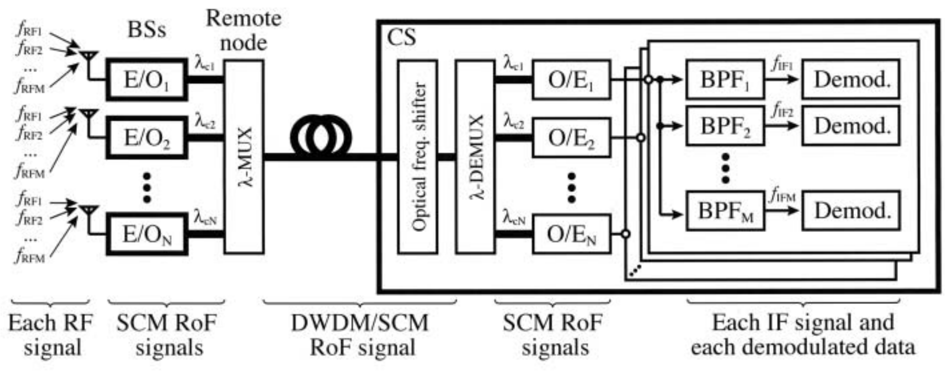

Fig.2 Configuration of an optical-frequency-interleaved DWDM/SCM RoF system

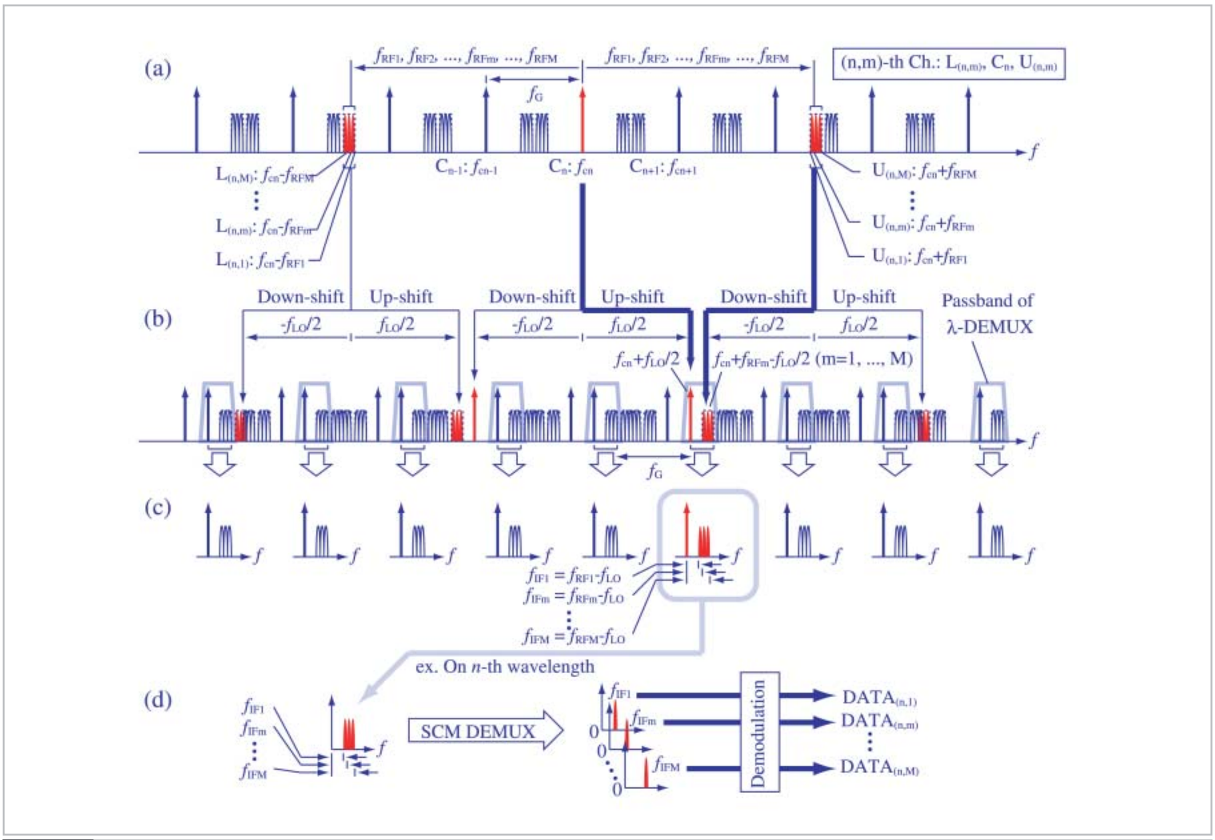

Fig.3 Spectrum design

(a) DWDM/SCM RoF signals, (b) frequency-shifted DWDM / SCM RoF signals and bandwidth of λ-DEMUX, (c) demultiplexed optical signals, and (d) demultiplexing SCM IF signal and its demodulation

example) close to each other as shown in Fig. 3(b)[6]. Next, each pair of the closely aligned components of $f_{cn}+f_{LO}/2$ and $f_{cn}+f_{RFm}-f_{LO}/2$ (m = 1, 2, ..., M) is filtered out by a wavelength demultiplexer (λ-DEMUX) as shown in Fig. 3(c). And then each optical signal is photodetected to generate the desired SCM IF signal in the microwave band ($f_{IFm}=f_{RFm}-f_{LO}$, m = 1, 2, ..., M). Finally as shown in Fig. 3(d), the SCM IF signal is separated to individual IF signals and they are individually demodulated. Thus, the photonic downconversion can be performed even in the optical-frequency-interleaved DWDM / SCM RoF system.

3 Experiment

The experimental setup is shown in Fig. 4. Optical carriers at 1552.12 nm [= c/f_{c1}], where c is the velocity-of-light in the vacuum, and 1551.92 nm [= c/f_{c2}] (spaced by 25 GHz [= $f_{c2}-f_{c1}$]) from tunable laser sources (TLS_1 and TLS_2, respectively) were independently modulated with 60-GHz-band electroabsorption modulators (EAM_1 and EAM_2, respectively) by an SCM RF signal. The SCM RF signal consisted of 59.6-GHz [= f_{RF1}] and 60.0-GHz [= f_{RF2}] signals carrying independent 155.52-Mb/s DPSK pseudo random bit sequences (PRBSs) of $2^{23}-1$. A 100-m-long SMF (short) was used to uncorrelate both DWDM channels for 155.52-Mb/s data. Therefore, it is presumed that all four data are statistically uncorrelated. Two SCM RoF signals generated in the BSs were power-combined by a 3-dB optical coupler, resulting in the desired optical-frequency-interleaved DWDM / SCM RoF signal. It was transmitted over 25-km-long SMF (long) to the CS. Here, a variable optical attenuator (VOA) was used to control the received optical power for the measurement. To achieve the desired shift in optical frequency as mentioned in the previous section, a $LiNbO_3$ Mach-Zehnder modu-

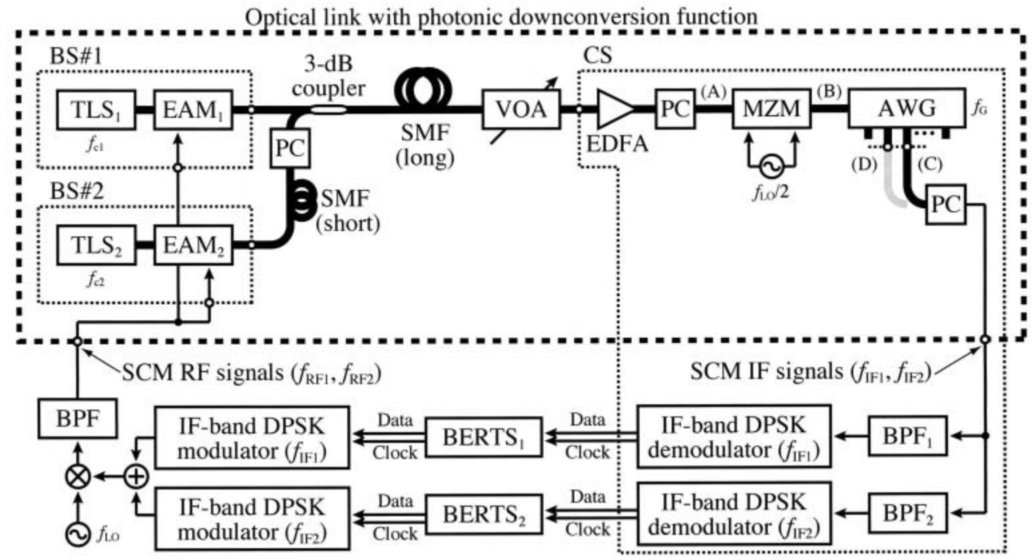

Fig.4 *Experimental setup*

lator (MZM) acts as a carrier-suppressed double sideband (DSB-SC) modulator[5][6]. The received optical signal was amplified by an Erbium-doped fiber amplifier (EDFA), polarization-controlled to match the polarization axis of the MZM with a polarization controller (PC), and put into the MZM. The polarization-matched optical signal was frequency-shifted in the optical domain, and put into a following 25-GHz-spaced arrayed waveguide grating (AWG). The closely aligned signals of ($f_{c1}+f_{LO}/2$ and $f_{c1}+f_{RFm}-f_{LO}/2$) and ($f_{c2}+f_{LO}/2$ and $f_{c2}+f_{RFm}-f_{LO}/2$) were filtered out individually by the different ports of the AWG, and then photodetected individually to generate the photonic-downconverted SCM IF signals. Here, the shifting frequency, $f_{LO}/2$, was 28.5 GHz. Each photonic-downconverted SCM IF signal was channel-separated and then individually demodulated to recover the 155.52-Mb/s data.

Figures 5(a) and (b) show the measured optical spectra at points of (A) and (B) in Fig. 4, respectively. From Fig. 5(b), each optical component was successfully down- and up-shifted by an amount of 28.5 GHz, compared with Fig. 5(a).

Figures 6(a) and (b) show the measured optical spectra at points of (C) and (D) in Fig. 4, respectively. For both cases, two groups of optical components of $f_{cn}+f_{LO}/2$ and $f_{cn}+f_{RFm}-f_{LO}/2$ (m =1, 2) were successfully filtered out. As shown in the upper illustration, the extracted signal has three components; a carrier and two sidebands. The two sidebands components are separated by 2.6 and 3.0 GHz

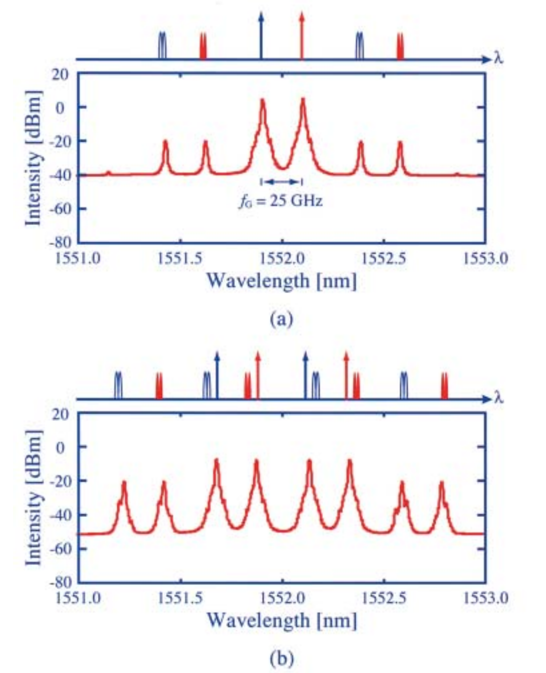

Fig.5 *Optical spectra measured*

(a) at the input of MZM and (b) at the output of MZM from the carrier. The suppression ratios over 25 and 35 dB were achieved for (1, m)-th and (2, m)-th channels, respectively. The suppression ratio depended on the suppression characteristics of AWG used in our experiment.

Figure 7 shows the measured electrical spectra of photonic downconverted SCM IF signals as well as the passband of BPFs for separating SCM channels. As shown in these figures, the photodetected signals occurred in the microwave frequency band as expected. Their central frequencies were 2.6 and 3.0GHz. They also successfully fell into the predetermined BPF_1 and BPF_2 passbands, whose 3-dB bandwidth was 234 MHz. And we measured the filtered IF signals without the payload data and confirmed that their spectrum line-width was very narrow with no laser phase noise effect. This result shows that the original SCM-RF signals at 59.6 and 60.0GHz were successfully frequency-downconverted to the desired SCM-IF signal at 2.6 and 3.0GHz through the optical link for both DWDM channels.

To investigate the system performance, bit error rates (BERs) for all channels transmitted over 25-km-long SMF were also measured. The results are shown in Fig. 8. The BERs of 10^{-9} for all channels were simultaneously achieved at the total received optical power of −17 dBm at the input of the EDFA. Some power penalty was observed. It is due to both the polarization mismatching and the different modulation index caused by the different conditions of optical modulation, which depends on the wavelength of the optical carrier, the bias voltage of EAMs, the reflection characteristics of RF port in EAMs, and modulating power of the input SCM RF signal. No BER floor was also observed within the measured power range. We have also verified that there was no difference of system performances between single-channel and two-channel DWDM transmissions. This shows that the crosstalk of 25 and 35 dB is negligible when the BER is 10^{-9}.

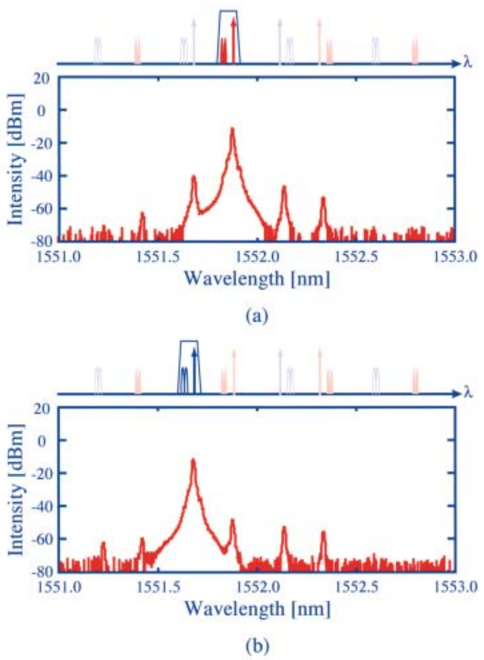

Fig.6 *Optical spectra measured at the output of AWG for*
(a) (1, m)-th channel and (b) (2, m)-th channel

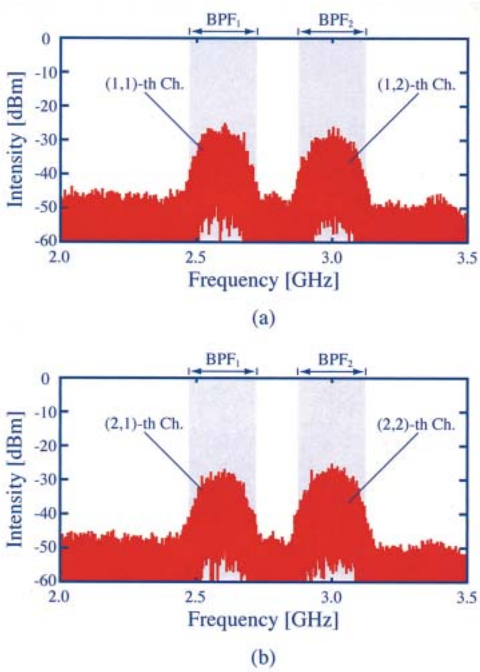

Fig.7 *Electrical spectra measured at the output of PD for*
(a) (1,m)-th channel and (b) (2,m)-th channel

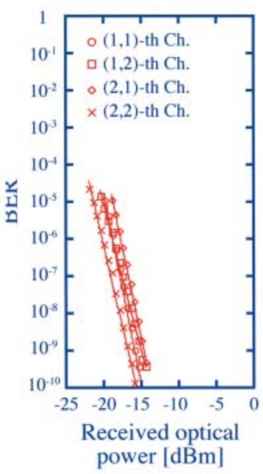

Fig.8 *Measured bit error rates*

4 Conclusions

We have described a photonic downconversion technique applied for optical-frequency-interleaved DWDM/SCM mm-wave-band RoF systems. The photonic downconversion technique was carried out for a lump of all uplink DWDM signals at a CS. Each channel was optically separated, photodetected, and demodulated individually without serious signal degradation due to the fiber dispersion effect. Error-free 25-GHz-spaced two-channel DWDM transmission and demultiplexing of two-channel SCM 60-GHz-band RoF signals carrying independent 155.52-Mb/s-DPSK data over 25-km-long SMF have been successfully demonstrated without serious crosstalk.

This technique will be a fundamental one for creating "smart radio wave environment" and keeping the system cost low even if demand of broadband wireless access increases in future.

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