channel signal and to block the unwanted signals and to further suppress the amplified spontaneous emission of the EDFA. The maximum size of this hybrid star coupler is determined by the performance of EDFA's and WDM multiplexers, the link attenuation of the network, and the receiver's dynamic ranges. Utilization of fiber amplifiers with high output saturation power will help the realization of the larger star network.

Besides the great saving of the required total fiber length and conduit length, there are other important advantages using a hybrid active star coupler. First, the inherent splitting and excess losses of the coupler can be compensated, at least to some degree, due to incorporating EDFA in the active central node. Second, the difficulties associated with constructing a large single star coupler for networks with a large number of users are alleviated. Finally, this configuration is independent of the gained fiber and pump wavelength, and only the associated WSC's should be replaced if pump wavelength is changed.

In conclusion, we proposed an efficient configuration of the hybrid-structured star coupler/network incorporated with fiber amplifiers. Besides the great saving of the required total fiber length and conduit length, this hybrid star coupler is easier to construct and more cost-effective for optical WDM/FDM networks.

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High-Speed Bidirectional Four-Channel Optical FDM-NCFSK Transmission Using an Er^{3+}-Doped Fiber Amplifier

Wann-Yih Guo and Yung-Kuang Chen

***Abstract*—A four-channel optical FDM-NCFSK bidirectional transmission experiment using an Er^{3+}-doped fiber amplifier at 1.7 Gb/s for 100 km fiber length is demonstrated. Using commercial DFB LDs, a received power of −35 dBm at 10^{-9} BER is obtained, and the dispersion degradation over 100 km bidirectional transmission is negligible. With channel spacing of about 30 GHz, the differential power penalty is about 0.1 dB.**

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INTRODUCTION

THE use of optical frequency division multiplexing (FDM) technique is very attractive for the future lightwave communication system, including subscriber and trunk transmission networks. Noncoherent frequency-shift-keying (NCFSK) is particularly preferable because of the low dispersion penalty for long-haul transmission and large channel capacity [1], [2], which can be simply achieved by using a single narrow-band optical filter to select "1" tone of modulated FSK signals and to convert FSK signals into amplitude-shift-keying (ASK) signals for direct detection [3], [4]. Thus, NCFSK lightwave system with optical amplifier and tunable optical filter has been intensely

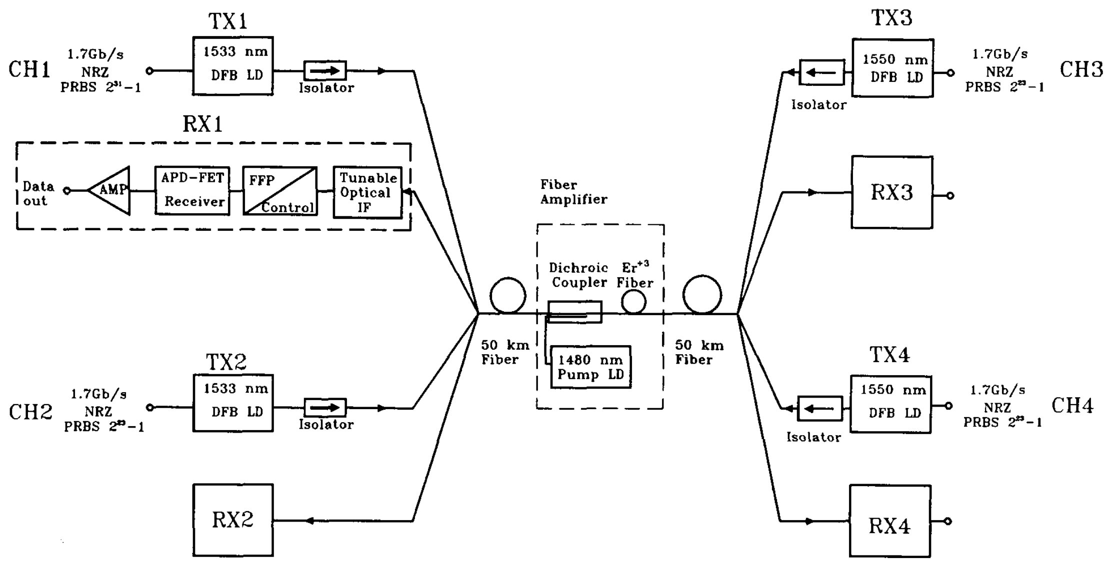

Fig. 1. The experimental setup of a four-channel optical FDM-NCFSK bidirectional transmission.

studied to improve receiver sensitivity and channel selectivity, which is comparable to coherent system and is simpler and more field-worthy [5]–[7]. To date several demonstrations of multichannel amplification using fiber amplifier have been reported [8], [9], and a two-channel bidirectional transmission at OC-12 with channel spacing of 3–4 nm using a fiber amplifier has also been investigated [10].

In this letter, we have successfully demonstrated a four-channel optical FDM-NCFSK bidirectional transmission using a fiber amplifier at the bit rate of 1.7 Gb/s and over the fiber length of 100 km. A received power of -35 dBm at the bit-error-rate (BER) of 10^{-9} and negligible dispersion degradation over 100 km bidirectional transmission have been obtained. With channel spacing of about 30 GHz, the differential power penalty is about 0.1 dB.

EXPERIMENTAL SETUP

The basic configuration of optical FDM-NCFSK bidirectional transmission experiment was shown in Fig. 1. Four commercial single-electrode DFB LD's, with wavelengths of two near 1533 nm at one side and two near 1550 nm at the other side, were directly modulated with FSK format at 1.7 Gb/s by $2^{31} - 1$ or $2^{23} - 1$ NRZ pseudorandom data. In this experiment, the channel spacing between CH3 and CH4 was controlled at 30 GHz. The FSK tone spacing for different transmitter was 8–9 GHz for 11–15 mA laser modulation. The laser outputs were passed through optical isolator individually and combined with a 4×1 single-mode coupler.

Then the combined outputs on each side were transmitted through a 50 km single-mode fiber and amplified by a fiber amplifier which was pumped with an 1480 nm LD. The input power, for each channel, of fiber amplifier was about -20.3 dBm for 1533 nm channels and about -18.6 dBm for 1550 nm channels, respectively. Unsaturated fiber-to-fiber gains at 1533 nm and 1550 nm were about 22 dB and about 19 dB, respectively. No optical isolators were placed before or after the fiber amplifier for the sake of bidirectional transmission. Thus, in this experimental setup, the pump beam in the fiber amplifier was forward-propagating with 1533 nm input signals and backward-propagating with 1550 nm input signals, respectively. Total input powers to the fiber amplifier were -13.4 dBm. As both channel spacings controlled at 30 GHz, a saturated gain of about 14 dB was obtained.

Furthermore, the outputs of the amplifier were transmitted through another 50 km single-mode fiber and splitted to the transmitters (TX's) and receivers (RX's). As connecting with optical isolator, the transmitter was not disturbed by the splitted signal or other optical reflections. At the receiving end, a tunable optical interference filter (IF) with a 3-dB passband of 3.5 nm was used to filter out additional amplified spontaneous emission (ASE) noise, pump light, and unwanted signal. An automatically controlled fiber Fabry–Perot (FFP) tunable optical filter was further used for FSK and ASK conversion, which induced a total fiber-to-fiber loss of about 6 dB, then the converted ASK signals were directly detected by a commercial 1.7 Gb/s APD-FET receiver with bandwidth of 1.2 GHz and the sensitivity of -35.6 dBm (at 10^{-9} BER). The FFP has a finesse of 140 and a 3-dB bandwidth of 5 GHz. The output of APD-FET receiver was sent to a low noise electric amplifier and to BER tester. In this experiment, all optical components were connected with commercial PC type connectors ($>$ 40 dB return loss).

RESULTS AND DISCUSSION

In the FSK-to-ASK direct-detection scheme, the "1"s and "0"s of single channel must be cleanly separated so that the Lorentzian-shape FFP optical filter can unambiguously transmit a selected "1" tone and block a rejected "0" tone. After transmission through 100 km, the BER data of CH1 for single channel and for four-channel bidirectional transmission with 60 GHz channel spacing between CH1 and CH2 are shown in Fig. 2; the inset open-eye diagram represents a BER of 1×10^{-11} for CH1 signal in four-channel 100 km bidirectional transmission. The received power of CH1, at 10^{-9} BER, for four-channel bidirectional transmission is about -35 dBm. Based on the theoretical model of optical amplifier [11], we may estimate the power penalty to be about 0.1 dB, which is caused by the ASE noise in the fiber amplifier (mostly contributed by the signal-spontaneous beat noise). It is noted that the BER data of single channel is degraded about 0.5 dB. As further measuring the relative intensity noise (RIN) of selected amplified signals of CH1, we find that the RIN ($f = 0$ Hz) of about -106 dB/Hz of single channel transmission fluctuates more severely and is about 5 dB higher than that of four-channel transmission. This is due to optical reflections, including multiple reflections and Rayleigh scattering, which degrade high speed system employing in-line optical amplifier [12]. The higher gain the fiber amplifier has, the more severe degradation the optical reflections cause, unless optical isolators are used. In our experiment, the gains of EDFA for four-channel bidirectional transmission and single channel transmission are 14 dB and 19 dB, respectively. Thus, the system performance for single channel transmission is undoubtedly degraded.

Fig. 3 is the plot of BER data of CH1, with various channel spacings, for four-channel 100 km bidirectional transmission. The power penalty will increase with the decrease of the channel spacing. This is due to the slow cutoff of the Lorentzian-shape FFP filter, which does not totally reject all unwanted tones; as channel spacing decreases, more power from CH2 is transmitted through the filter, thus contributing to a power penalty. We find the power penalty will increase up to 3.1 dB at channel spacing of 12.8 GHz, corresponding to 7.53 B, where B is the bit rate. In Fig. 4, the differential power penalty [1], Pd, is measured as a function of channel spacing, *Fc*, for four-channel 10 m and 100 km bidirectional transmission, respectively. The differential power penalty is defined to be the increase in power necessary to maintain a BER of 10^{-9} while detecting the "1" tone of CH1. We find that the differential power penalties for 10 m and 100 km bidirectional transmission are almost the same. Thus, the chromatic dispersion penalty is negligible. As depicted by the data of Fig. 4, a low differential power penalty, 0.1 dB, is measured for channel spacing of about 30 GHz, corresponding to 17.6 B. This channel spacing is much greater than the optimal value derived from an analysis of an undistorted FSK signal converted into ASK format [1].

CONCLUSIONS

We have demonstrated a bidirectional transmission experiment with a capacity of 6.8 Gb/s over 100 km fiber length using four-channel optical FDM-NCFSK and employing an in-line fiber amplifier. Using tunable optical IF and FFP filters, the ASE noise of fiber amplifier can be filtered out, and the FSK signal of desired channel can be converted into ASK signal. The received power at 10^{-9}

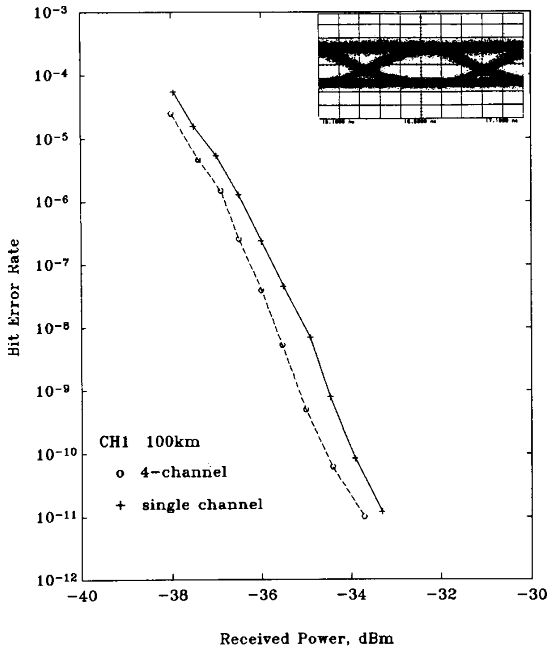

Fig. 2. BER data of CH1 for single channel and four-channel bidirectional transmission with 60 GHz channel spacing of CH1 and CH2. Inset: eye diagram representing 1×10^{-11} BER for CH1 100 km bidirectional transmission.

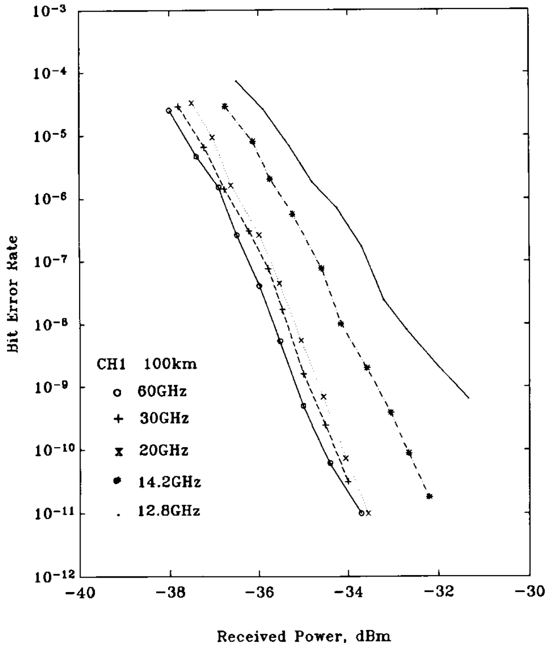

Fig. 3. BER data of CH1 with several channel spacings for four-channel 100 km bidirectional transmission.

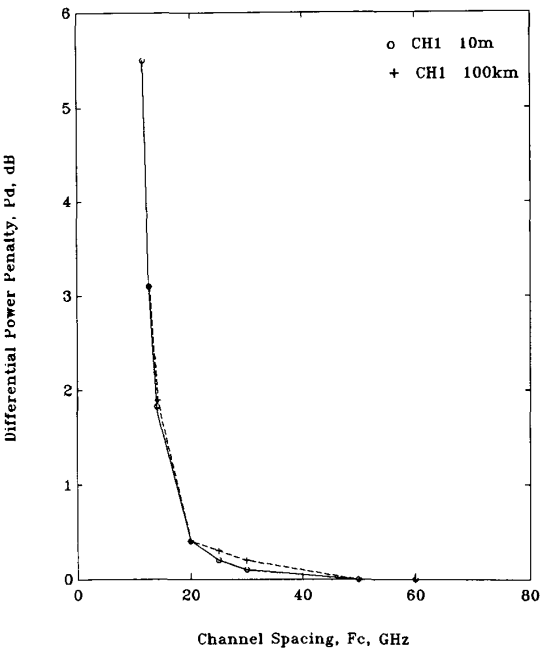

Fig. 4. Differential power penalty of CH1 versus channel spacing, *Fc*, for four-channel 10 m and 100 km bidirectional transmission, respectively. The 0 dB level represents the lowest measured received power, at 10^{-9} BER, for four-channel bidirectional transmission.

BER is -35 dBm. The power penalty induced by chromatic dispersion is negligible because the laser spectrum under low driving current is compact and is further narrowed down by a narrowband FFP filter. Owing to the degradation of output signals of fiber amplifier caused by the optical reflections, a power penalty of 0.5 dB has been observed. With channel spacing of about 30 GHz, the differential power penalty is about 0.1 dB.

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