Hybrid Transmissive Optical Star Couplers with Gain Using Fiber Amplifiers

Yung-Kuang Chen, Sien Chi, and Jy-Wang Liaw

Abstract—**A hybrid transmissive star coupler incorporating fiber amplifiers for WDM / FDM networks is proposed. It is found that the total fiber length and conduit length required for this hybrid star coupler / network can be reduced tremendously as comparing with either the centralized or the distributed cases. Furthermore, this coupler is easier to construct and more cost-effective.**

OPTICAL star networks have the potential to provide very large throughput, and they are expected to find widespread application in upgrading existing networks as well as photonic networks [1]–[3]. In many practical networks, users are geographically distributed in clusters such as several floors in a building, several buildings in a campus, etc. In this case, a distributed star coupler incorporating with erbium-doped fiber amplifiers (EDFA's) can be adopted not only to compensate the inherent splitting and excess losses of the star coupler effectively, but also to save the total fiber length and conduit length [4]–[6]. Unfortunately, both the total fiber length and conduit length required to build up the distributed star network increase drastically when the number of distributed nodes becomes larger, and this limits the cost-effectiveness of the distributed star network. In this letter, we propose a hybrid-structured star coupler to resolve the aforementioned problem. The configuration, characteristics, and features of this coupler are investigated.

Assume there are N users distributed in n clusters geographically over n nodes (i.e., locations); each node has N_0 users, where $N_0 = N/n$ and $2 \leq n \leq N/2$. Then, the proposed single-mode fiber-optic hybrid $N \times N$ star coupler, base on using shorter fiber and conduit length and fewer EDFA's, used to interconnect these users is shown in Fig. 1. It is composed of n $N_0 \times 1$ WDM multiplexers, one $n \times n$ passive star coupler, n fiber amplifiers, and n $1 \times N$ tree couplers. In fully transparent WDM/FDM star networks, each user transmits its information on a fixed unique wavelength. Therefore, for the N users supported by this network, N wavelengths and n different multiplexers are needed. The fully single-mode multichannel WDM multiplexer employs diffraction grating design and can achieve channel spacing on the order of 1 to 2 nm such that they can accommodate 40 to 50 channels with the excess loss of about 7 dB per channel [7]. Each $1 \times N_0$ tree coupler can be constructed by $\log_2(N_0)$ stages of 1×2 3-dB couplers cascaded in a tree-like structure with a total number of $N_0 - 1$ when N_0 equals arbitrary power of two, and can be constructed by combining 1×2 3-dB couplers, 1×3 couplers, and/or 1×7 couplers, etc., when N_0 is not a number of power of two. Each EDFA is composed of an erbium-doped fiber, a pump laser source, a wavelength selective coupler used as a pump/signal combiner, and an optical isolator used to avoid optical reflections.

In this hybrid star coupler, the interconnections between n distributed passive nodes and an active central node are always two fibers in one conduit, one fiber for transmission to the input port of the EDFA and the other for reception from the output port of the $n \times n$ central-node coupler. If these N users are distributed uniformly around a circle of diameter D over n locations, then the numbers of fibers and conduits required for this star network are $2n$ fibers of total length nD and n conduits of total length $nD/2$, respectively. However, the total fiber length and conduit length are ND and $ND/2$, respectively, for the centralized case [8], and are $(N/n)\sum_{p=1}^{n-1}(D/\sqrt{2}) \cdot \sqrt{1 - \cos(2p\pi/n)}$ and $(n/2)\sum_{p=1}^{n-1}(D/\sqrt{2}) \cdot \sqrt{1 - \cos(2p\pi/n)}$, respectively, for the distributed case [4], [6]. Fig. 2 shows the normalized total fiber length (normalized to D and in the logarithm scale) versus the size of star coupler N, either $N = m^2$ or $N = 2m^2$ and m is a number of power of two, with node numbers $n = 2$ and $n = m$ for these three types of star coupler. For example, the total fiber length required for the hybrid 64×64 star coupler with $n = 8$ is $8D$, which is 19.89% and 12.5% for those of the equivalent distributed and centralized cases, respectively. For the hybrid 1024×1024 star coupler with $n = 32$, the required total fiber length is $32D$, which is 4.91% and 3.13% for those of the equivalent distributed and centralized cases, respectively. Fig. 3 shows the normalized total conduit length versus N with $n = 2$ and $n = m$ for these three types of star coupler. Similarly, it is found that the total conduit length required for the hybrid star coupler can be also reduced greatly as compared to the other two cases. Hence, the total fiber and conduit length can be reduced tremen-

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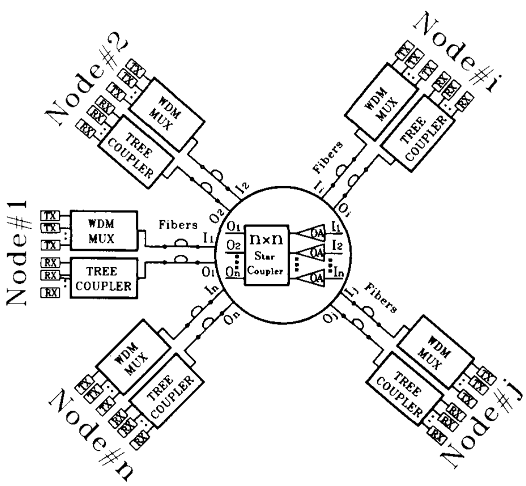

Fig. 1. The proposed hybrid $N \times N$ star coupler is composed of n $N_0 \times 1$ WDM multiplexers, one $n \times n$ passive star coupler incorporated with n fiber amplifiers, and n $1 \times N_0$ tree couplers. WDM MUX: the $N_0 \times 1$ WDM multiplexer, OA: the optical fiber amplifier.

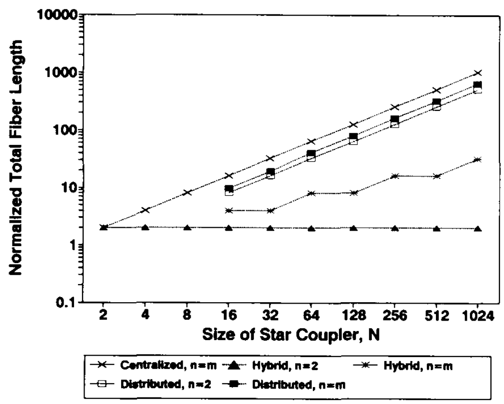

Fig. 2. The normalized total fiber length versus the size of star coupler, N, with $n = 2$ and $n = m$ for the centralized, distributed, and hybrid star couplers.

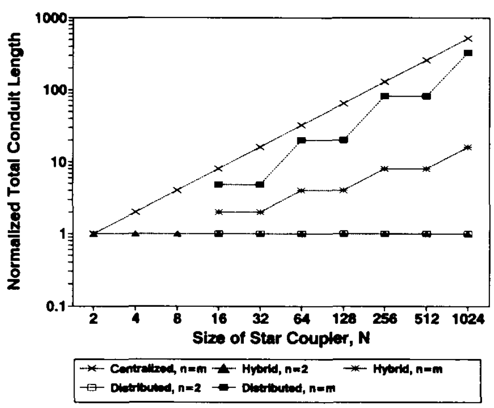

Fig. 3. The normalized total conduit length versus N with $n = 2$ and $n = m$ for the centralized, distributed, and hybrid star couplers.

dously for the proposed hybrid configuration of star coupler; both of them are independent of N but depends only on n, and this increases the cost-effectiveness significantly.

The total transmission loss (i.e., the link attenuation), L_T (dB), between two users in the same or different node is $L_T = 10[\log(L_{\mathrm{MUX}}) + \log(n) + \log(L_{\mathrm{EDFA}}) + \log(N_0)] + \alpha D \cdot \mathrm{dB}$. Here L_{MUX} is the excess loss of each WDM multiplexer; L_{EDFA} is the insertion loss of a WSC (≈ 0.5 dB), and an isolator (≈ 0.5 dB), and two splice losses between the EDF and the standard single-mode fiber (≈ 1.0 dB) in each EDFA. $10\log(n) + 10\log(N_0) = 10\log(N)$ is the splitting losses of the $n \times n$ and $1 \times N_0$ coupler, respectively. αD is the fiber transmission loss of this network link, where α is the fiber loss per km. Here L_T is about $10\log(L_{\mathrm{MUX}}) - 7 \cdot \mathrm{dB}$ larger than that of the centralized and distributed cases. Moreover, L_{MUX} is not proportional to N; it is a finite loss even for larger N with $N/n = 50$ [7].

The EDFA with its wide gain profile is a broad-band optical amplifier which is suitable for WDM applications. One of the impairments of multichannel amplification in semiconductor optical amplifiers (SOA's) is the intersymbol interference crosstalk due to gain saturation introduced by signals in neighboring channels. However, the comparatively long recovery time in the 1-ms range, which makes the EDFA immune to crosstalk patterning effects over a wide range of bit rates, shows the advantage of EDFA's over SOA's in TDM or WDM systems using the ASK modulation format [9]. For densely packed WDM systems, the long gain recovery time is also an indication of the EDFA immunity to intermodulation distortion effects.

In the broadcast operation mode of this hybrid star coupler, the maximum number of input WDM signals being amplified by each EDFA is N/n. When the input power level of all traveled signals is higher than, for example, -10 dBm, the EDFA may act as a power amplifier and the small signal gain will be replaced by the saturation gain. The net gain from one user to another is $10\log(G) - L_T \cdot \mathrm{dB}$ but there are some variations of net gain due to the EDFA with different input channel signals. Furthermore, it is desirable to consider the signal-to-noise ratio (SNR) of the star network. The selected signal S is attenuated by the losses of a WDM multiplexer, a WSC (I_{WSC}), an isolator (I_{ISO}), an $n \times n$ star coupler, the fiber loss, and a $1 \times N_0$ tree coupler. Assume all EDFA's have the same optical gain (G) and noise power (σ^2) in forward pumping scheme, then the SNR (in linear scale) for a user from a different user, SNR_H, is

$$\mathrm{SNR}_H = \frac{G \cdot S}{n \cdot \sigma^2 \cdot I_{\mathrm{WSC}} \cdot L_{\mathrm{MUX}} \cdot 10^{(\alpha D/20)}}. \tag{1}$$

Note that, with any finite loss, the smaller n gives rises to the higher SNR_H and the fewer numbers of EDFA's for a fixed N. At the receiving end, a tunable narrow-band optical bandpass filter is necessary to select the wanted 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

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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

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