Multiwavelength Line-Rate-Independent Optical Digital Cross-Connects Based on Low-Gain Fiber Amplifiers

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Abstract—**We experimentally demonstrated a multiwavelength, line-rate independent optical digital cross-connect system (DCS) by using cascaded low-gain erbium-doped fiber amplifiers as the switching elements in a dilated Benes architecture.**

I. INTRODUCTION

A DIGITAL cross-connect system (DCS) automatically cross-connects constituent signals according to an electronically alterable memory map. Unlike a conventional circuit switch, a DCS is a non-blocking "slow" switch with a connection duration of hours or months, and switches much higher rate signals. Present DCSs are designed to terminate a fixed line-rate optical signal, and the cross-connect function is performed in the electrical domain. Consequently, when higher line-rates are required in the future, the original DCS may have to be entirely replaced. To overcome this problem, we propose and demonstrate a line-rate-independent, multi-wavelength space-division optical DCS based on low-gain erbium-doped fiber amplifiers (EDFAs). This DCS provides a net optical gain, supports point-to-point, multicast and broadcast connectivity, and uses a minimum number of basic EDFA switching units. Since DCS is mainly used for 1) efficient network utilization, 2) network restoration, and 3) customer control and management, fast switching is generally not required. Therefore, switching units based on EDFAs are more suitable than those based on either semiconductor optical amplifiers [1], [2] (which may have severe saturation-induced pulse distortion and multi-wavelength crosstalk), or $LiNbO_3$ waveguide switches [3] (which have high insertion loss, high crosstalk, and require high driving voltages). Furthermore, in selecting the appropriate DCS switch architecture, we note that the DCS network functions allows $\simeq 50$ ms [4] reconfiguration time. Therefore, a rearrangeable nonblocking architecture is selected as will be described in Section III.

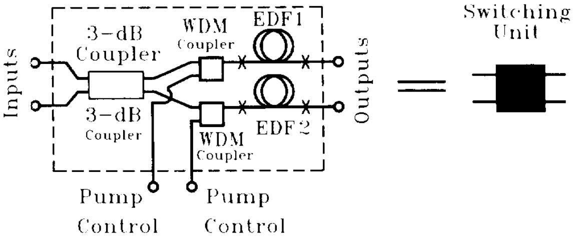

Fig. 1 The erbium-doped fiber amplifier (EDFA) based switching unit.

II. DEVICE CONSIDERATIONS

The implementation of an EDFA switching unit is shown in Fig. 1. It is based on a net gain from the amplifier when pumped to overcome total losses, and a high loss to avoid crosstalk. The high loss is resulted from the absorption effect of the doped fiber when unpumped and the insertion loss of other components in the amplifier. The EDF length is determined so that with the amplifier unpumped the total loss through each stage is greater than 22 dB, i.e., the crosstalk is smaller than -25 dB (the additional 3 dB is from the 2×2 coupler), and with the amplifier pumped to achieve 4 to 5 dB gain (enough for each stage to be lossless). The pump light for each EDFA can be switched on or off via a mechanical optical switch or via direct pulse-code modulation [5]. We employ the low-gain EDFAs for three reasons: 1) a low-gain amplifier provides nearly wavelength-independent gain to perform multi-wavelength amplifications; 2) it provides low amplifier-induced beat-noise; and 3) it provides substantial immunity to reflection-induced degradations [6].

III. DILATED BENES DCS

Table I lists the architectures of all nonblocking DCSs which can be implemented with low-gain EDFAs and 3-dB optical couplers. These architectures include the distributed-gain matrix-vector multiplier (DGMVM) crossbar [2], dilated Omega [7], dilated Benes [7], Clos [8], rectangular crossbar [9], and double crossbar [10]. For each of these $N \times N$ architectures, Table I gives the different degrees of nonblocking properties and the number of required EDFAs and 3-dB couplers. Both the strictly nonblocking dilated Omega network (the "dilated Omega-I") and the rearrangeably nonblocking dilated Omega network (the "dilated Omega-

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TABLE I
ARCHITECTURES AND CONSTRUCTION COMPARISON OF All NONBLOCKING EDFA-BASED DCSs.

Nonblock-ingness	Strickly Nonblocking			Rearrangeably Nonblocking			Nonblocking in the Wide Sense	
DCS Network	DGMVM Crossbar	Dilated Omega-I	Clos-I	Clos-II	Dilated Omega-II	Dilated Benes	Rectangular Xbar	Double Crossbar
EDFA Stages	$2\log_2(N)$	$2\log_2(N)$	$2m+4n-4^{@}$		$2\log_2(N)-1$		$2N-1$	$N+1$
Coupler Stages	$2\log_2(N)$	$2\log_2(N)+1$	$2m+4n-3^{@}$		$2\log_2(N)$		$2N-1$	$N+1$
Total EDFAs	$3N(N-1)$	$4N\log_2(N)$	$12(N)^{3/2*}$	$6(N)^{3/2\#}$	$2N[2\log_2(N)-1]$		$N(2N-1)$	$3N^2$
Total Couplers	$6N$	$2N\log_2(N)+N$	$6(N)^{3/2*}$	$3(N)^{3/2\#}$	$2N\log_2(N)$		N^2	$2N^2$

Notes:

@ Number of EDFA stages = 2n+2m+2r−4 = 2m+4n−4, number of coupler stages = 2n+2m+2r−3 = 2m+4n−3, if r=n for both Clos-I (m>=2n−1) and Clos-II (m>=n) DCSs.

* For Clos-I : total EDFAs = 6mN = $12(N)^{3/2}$, total couplers = 3mN = $6(N)^{3/2}$; if r=n, m=2n, and n= $N^{1/2}$.

\# For Clos-II : total EDFAs = 6mN = $6(N)^{3/2}$, total couplers = 3mN = $3(N)^{3/2}$; if r=n, m=n, and n= $N^{1/2}$.

II") are derived from conventional blocking dilated Omega network [7] by adding $\log_2(N)-1$ and $\log_2(N)-2$ extra stages of switching units, respectively. Note that the number of EDFAs in dilated Omega-I, dilated Omega-II, and dilated Benes grows proportional to $N\log_2 N$ as opposed to $N^{3/2}$ for the Clos network and N^2 for other architecture. Among various nonblocking switch architecture, we chose the dilated Benes architecture, as shown in Fig. 2 for an 8 × 8 network, to build an EDFA-based space-division optical DCS. A dilated Benes architecture was chosen because (a) it is rearrangeable nonblocking and has the superior modularity and scalability features, and (b) it uses a minimum number of EDFAs and provides the satisfactory crosstalk performance. The dilated Benes DCS is constructed with the inverse shuffle and the perfect shuffle connections recursively until 4 × 4 subnetwork are reached. The 4 × 4 subnetwork, in the last stage of the recursion, are constructed with two stages of 3-dB couplers and EDFAs. Each switching unit in the dilated Benes DCS is composed of a 1 × 2 (in the first stage) or a 2 × 2 (in the middle stages) 3-dB coupler followed by two separate EDFAs. The last stage in the architecture is simply composed of 2 × 2 3-dB couplers. The superior modularity and scalability feature for this network is due to its recursive construction and the inverse shuffle and perfect shuffle connections.

A dilated $N \times N$ Benes architecture require a total of $2N\cdot[2\cdot\log_2 N-1]$ EDFAs for an $N \times N$ DCS. This number is smaller than those of other nonblocking architectures, as shown in Fig. 3. The required number of 3-dB couplers in this architecture is $2N\cdot\log_2 N$ which is slightly more than that of the DGMVM crossbar architecture but less than those of all other architectures. An $N \times N$ dilated Omega-II switch network requires the same number of EDFAs and 3-dB couplers as that of the dilated Benes network, however, it uses the perfect shuffle connection patterns. For the dilated Omega-I DCS, $2\log_2 N+1$ stages of 3-dB couplers and $2\log_2 N$ stages of EDFAs are required, and there are N connecting paths can be made between any pair of endports to realize strictly nonblocking permutation. To be fault tolerant, an architecture must provide multiple paths between any pair of endpoints. There are N and $N/2$ paths between any pair of endpoints for dilated Omega-I, and dilated Omega-II / Benes DCSs, respectively. The failure of any single EDFA does not make either switch architecture inoperable, for any specific pairs of endpoints. Therefore, the architectures mentioned above (dilated Benes, dilated Omega-I, and dilated Omega-II) are fault tolerant from the standpoint of single EDFA failure. Furthermore, they all support point-to-point, multicast and broadcast communication connectivity.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In the experiment, the core size and the numerical aperture of our home-made EDF were 4.2 μm and 0.23, respectively. The length (4.5 meter) of the EDF was determined to give a 4 to 5 dB gain when pumped to overcome splitting loss, and a 22 dB loss when unpumped to avoid crosstalk. Two 980 nm laser diodes were used to provide the pump lights along the connecting path as indicated by the thick dark line shown in Fig. 2. The first laser with a 42 mW output power was split by a 1 × 8 coupler to provide about 5 mW to each of three front EDFAs, and the second laser with a 16 mW output power was split by a 1 × 2 coupler to provide about 7.8 mW to each EDFA

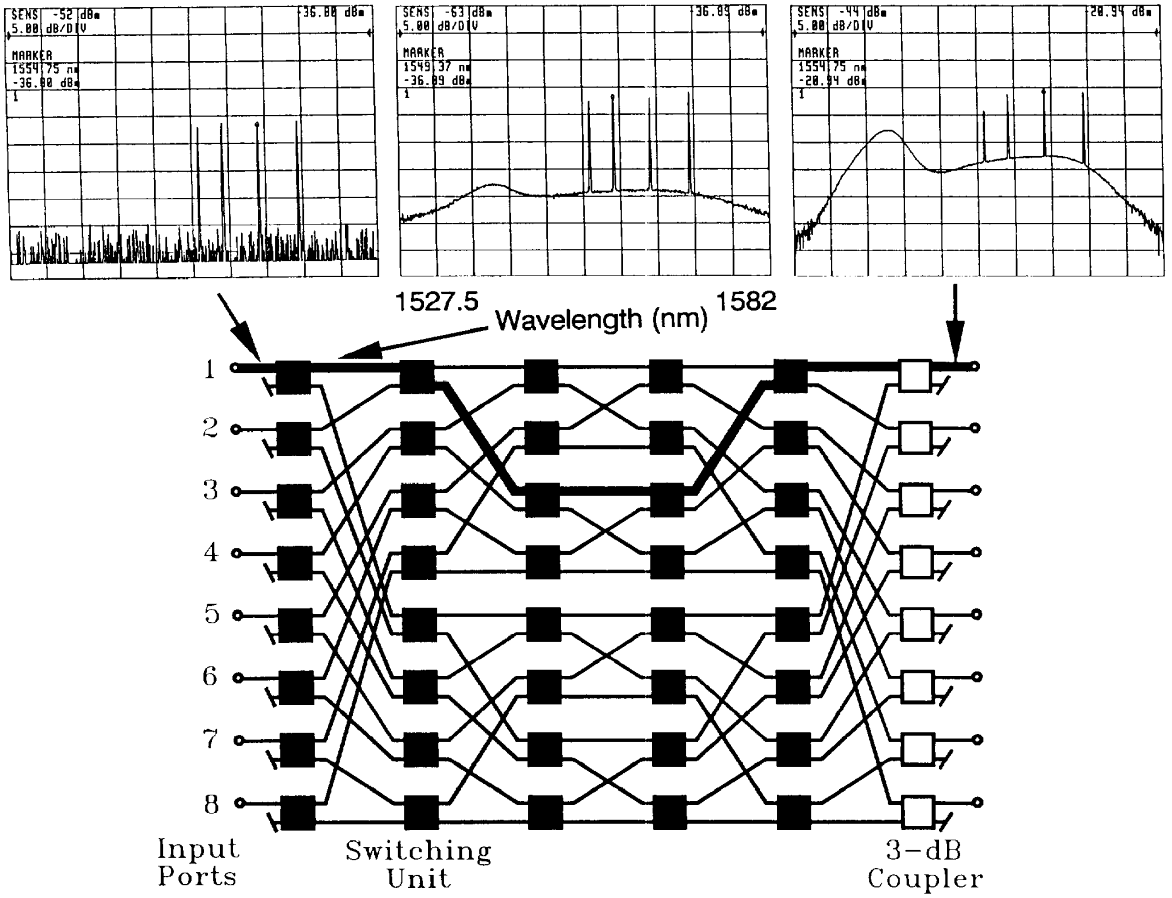

Fig. 2. An 8 × 8 dilated Benes DCS using EDFA-based switching units. The optical spectra of the four small-signal wavelengths at an input, and after the first and sixth stages of switching units are shown, respectively.

in the last two stages. In practical applications, however, each pump laser power should be shared by the switching units in each stage, i.e., column-wise instead of row-wise power sharing. This facilitates higher pump power adjustment in the last few stages to avoid gain saturation due to accumulated amplified spontaneous emission noise. To demonstrate a multi-wavelength signal transmission through the optical DCS, we used four DFB lasers with wavelengths of 1545.9 nm, 1549.3 nm, 1554.7 nm, and 1560.5 nm, respectively, as shown in Fig. 2. Both small and large signal conditions were tested. The input power of each wavelength was adjusted to be −35 dBm for the former case, and −12 dBm for the latter case. The optical spectra of the amplified small signals after the first and the sixth stages are shown in Fig. 2. The overall small-signal net gain for the four wavelengths ranges from 13 to 16 dB. Figs. 4(a) and (b) shown the spectra of the amplified large signals after the first and sixth stages, respectively. The overall net gain for the four wavelengths ranges from 1 to 5.5 dB. The fairly uniform gain in the ~15 nm range shows the feasibility of the low-gain EDFA-based multi-wavelength DCS.

Regarding the signal-to-noise ratio (S/N) degradation, the worst channel optical S/N of 10 dB in the small-signal case can be significantly improved if the DCS input signal levels can be increased by 10 dB or more from the original −35 dBm input level. Actually, a small signal level of −25 dBm per wavelength is more realistic because a typical 2.5 Gb/s receiver (thermal noise-limited) sensitivity is around −27 dBm. Input signal levels (to the DCS) lower than thermal noise-limited sensitivity cannot achieve low error rate performance. Of course, the penalty for obtaining a better optical S/N is a lower input dynamic range for the DCS.

Note that a key advantage of using dilated Benes architecture is that only one of the two input ports of each switching unit is active, this in turn ensures that the signal or ASE crosstalks from all previous stages are attenuated by an unpumped EDF in the previous stage (connected to the inactive port) by at least 25 dB (22 dB due to unpumped-EDF absorption and 3 dB due to the 2 × 2 coupler). Therefore, signal and ASE crosstalks can be considered negligible even when all other first stage input ports have signals present.

Note also that by "fault-tolerant", we originally meant, a single EDFA failure-tolerant instead of an entire switching unit failure-tolerant. But that is the case when the DCS laser wavelengths of an input port can collide with those of other

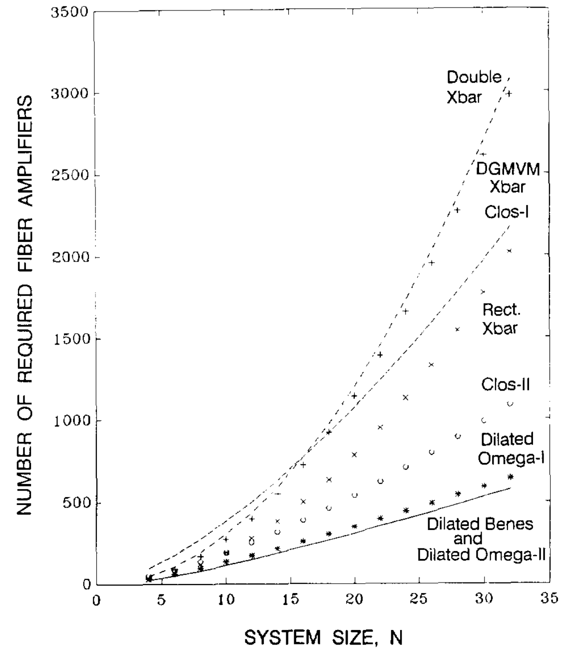

Fig. 3. The number of required EDFAs versus the size, N, of a DCS for various nonblocking DCS architecture.

input ports. If we assume, however, that each DCS input port has only one or two unique wavelengths, then we have a complete new dimension (wavelength) for tolerance. In other words, single (switching unit) fault tolerant is now feasible because each switching unit can take up to four wavelengths (one or two for the original signal wavelengths, and two or three for re-routed wavelengths from other failed paths).

V. CONCLUSION

We have experimentally demonstrated a multi-wavelength line-rate-independent space-division optical DCS using low-gain EDFAs without optical isolators and filters. We have also proposed the dilated Benes architecture as the basic structure for a rearrangeable nonblocking DCS that use a minimum number of EDFAs and a small number of 3-dB couplers. The proposed DCS may find important applications such as network restoration and efficient network utilization in multi-gigabit SONET networks.

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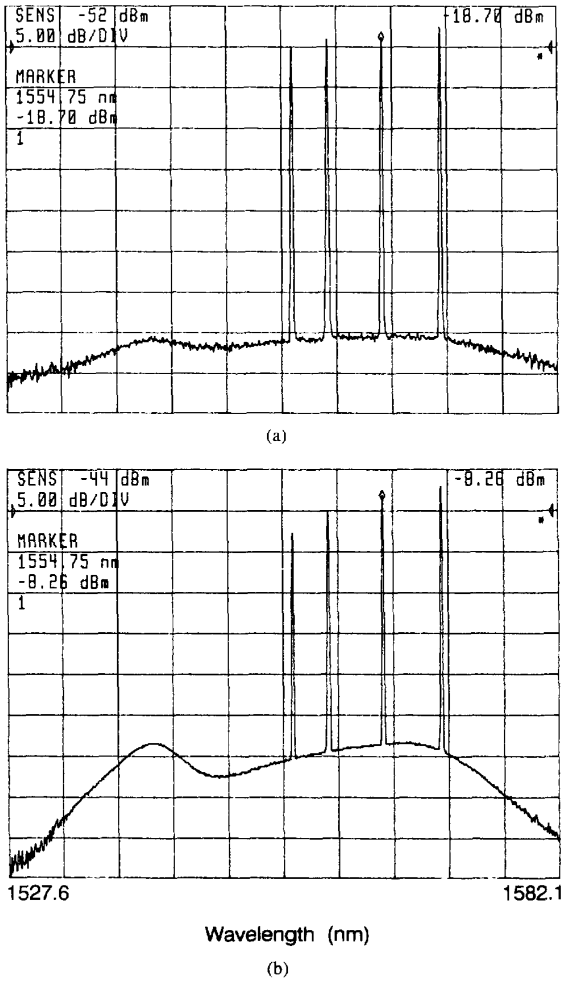

(a)

(b)

Fig. 4. The optical spectra of the four large-signal wavelengths after the first (a) and the sixth (b) stages of EDFA switching units.

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