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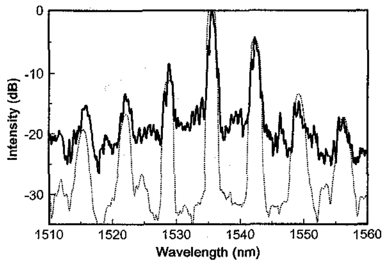
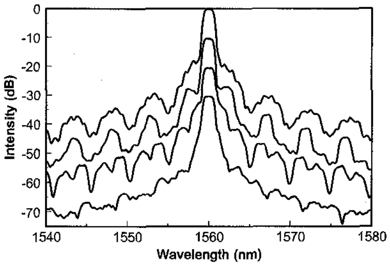


CWT2 **Fig. 2.** Measured (solid line) and calculated (dotted line) spectra of a demultiplexer with a constant stitching error resulted from FIB gain calibration error of 0.2%, which was intentionally introduced in the writing of the grating. The field size was 52 μm.



CWT2 **Fig. 3.** Simulated spectra for a maximum stitching error of 50 nm with different random sequences. The field size is 80 μm. For clarity the curves are displaced vertically by 10 dB from each other.

stitching error between adjacent fields. Further, the gain parameter controlling the FIB deflection amplitude needs to be calibrated in relation to the stage movement. A gain calibration error produces a constant stitching error.

We have developed a model that simulates the spectral characteristics of the demultiplexer including all of the above defects of the grating. It was found that constant stitching errors produce decaying periodic satellite peaks (Fig. 2). Random stitching errors resulting from stage movement inaccuracies can produce shoulders on both sides of the main peak, in addition to decaying irregular sidelobe structures (Fig. 3). For a field size of 80 μm and a maximum stitching error of 50 nm, the cross talk between adjacent channels can vary from −15 to −25 dB. This is in agreement with most of the spectra measured experimentally.

The pixelation effect due to the step size limit in the writing of the grating can produce a high background level that does not decrease in intensity with distance from the main peak.[6] This ultimately determines the limit of achievable cross talk level if the stitching errors as well as the background due to stray light are eliminated. A step size of 25 nm produces a background level of about −32 dB. By writing the grating with a state-of-the-art e-beam machine with a step size <5 nm, a wavelength demultiplexer with cross talk of <−45 dB is possible in principle.

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CWT3 **5:00 pm**

Influence of interferometric cross talk in a cascade of 10-Gbit/s wavelength routers and an improved Gaussian cross talk model

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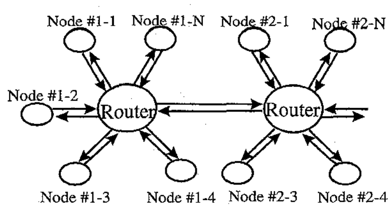
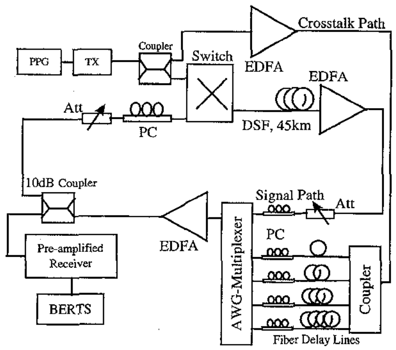
Integrated optical N × N wavelength routers based on arrayed-waveguide gratings (AWGs) are likely to become key devices in future wavelength-division multiplexing (WDM) networks.[1,2] A cascade of wavelength routers is formed when several N × N networks are interconnected as shown in Fig. 1. Due to the nonideal transfer function of physical AWGs, a node will receive not only the signal from the node it is connected to, but also cross talk at the same wavelength from the other nodes. In a cascade of AWG routers, the cross talk will accumulate and thereby limit the number of stages. The Gaussian cross talk model is considered to be a worst-case model when investigating multiple independent cross talk sources,[2–4] but higher power penalties than predicted by this model is found in Ref. 4 as well as in our work. We extend the model by including the signal extinction ratio and spontaneous emission from the optical preamplifier in our receiver. Experimentally, a recirculating loop is used for investigation of router cascades. Very good agreement is demonstrated between the measured penalty and the penalty predicted from our improved Gaussian cross talk model.

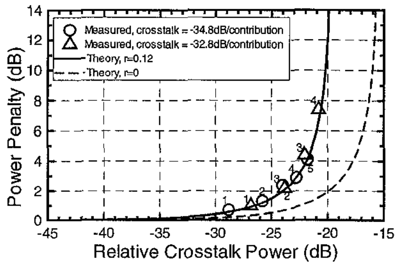
In our cross talk model, which includes signal-cross talk beat noise and signal-spontaneous emission beat noise, we assume that (1) the signal and all the cross talk contributions have the same polarization state (worst case); (2) the noise contributions are independent and can be described by Gaussian probability density functions; (3) optimized threshold is used. This leads to a new equation for power penalty versus relative cross talk ε and signal extinction ratio r:



CWT3 **Fig. 1.** Architecture of network using a cascade of routers.



CWT3 **Fig. 2.** Experimental setup for measuring the cascadability of routers. PPG: pulse pattern generator. TX: transmitter. Att: attenuator. PC: polarization controller. BERTS: bit-error-rate test set. DSF: dispersion-shifted fiber. AWG: arrayed waveguide grating.



CWT3 **Fig. 3.** Relation between power penalty and relative cross talk power. The number related to the symbols indicates the loop round trips corresponding to the number of cascaded AWG routers.

$$Penalty(dB) = -10 \log\left[1 - \frac{(1+r)Q^2\varepsilon}{(1-\sqrt{r})^2}\right] \quad (1)$$

Q is equal to 6 at BER = 10^{-9}.

Figure 2 shows the recirculating loop setup used for the investigation of the AWG router cascadability. The light from the transmitter modulated externally at 10 Gbit/s is divided into a signal part and a cross talk part. The cross talk part is amplified in an erbium-doped fiber amplifier (EDFA), split into four, and decorrelated using four fibers of different length in order to obtain independent cross talk contributions. The signal part is launched via the switch into the loop, which includes 45 km of dispersion-shifted fiber. Polarization controllers and an attenuator are put before the AWG router to achieve identical polarization states and approximately equal power at all inputs. The loop contains two EDFAs to compensate for the loss. A part of the signal (including cross talk) circulating in the loop is coupled into the optically pre-amplified receiver. Bit error rate is measured at optimized threshold.

Wavelength routers used in cascade should be carefully designed, because all cross talk contributions are accumulated in the cascade. Even for a low cross talk power of −34.8 dB per contribution, a power penalty of 4.1 dB is measured when cascading five routers, each adding four cross talk contributions. The measured penalty as a function of accumulated cross talk power is shown in Fig. 3 together with the penalty calculated from (1) assuming an extinction ratio of 0.12 (solid). Excellent agreement between experimental result and the new Gaussian model is observed. To show the influence of the signal extinction ratio, a curve of r = 0 (dashed) is also plotted in the same figure. It can be seen that for a penalty of 1 dB there is a 5 dB difference of cross talk power. This clearly shows the importance of including the signal extinction ratio.

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CWT4 **5:15 pm**

Multiwavelength dynamically selective cross-connect based on fiber Bragg gratings and optical switches

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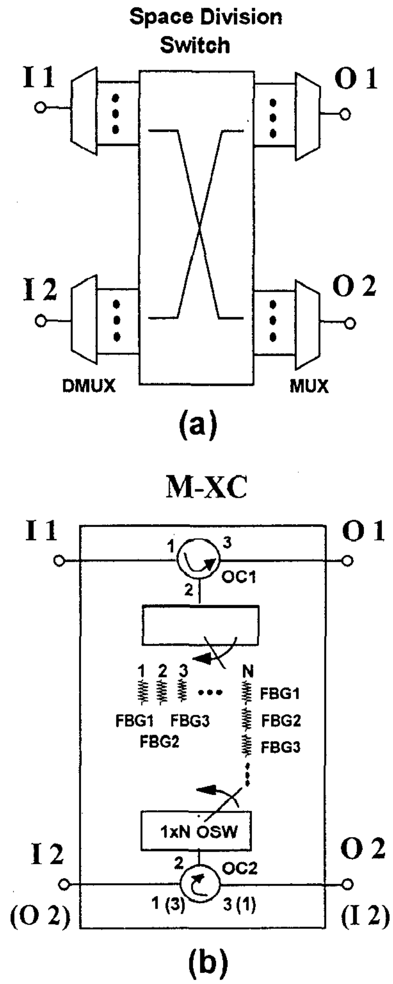
Multiwavelength cross-connect switch (M-XC) will play a key role in future optical multiwavelength wavelength-division multiplexing (WDM) networks.[1,2] The importance of the M-XCs, and the closed related WDM add drop multiplexer (ADM), is that they allow the optical network to be reconfigured on a wavelength-by-wavelength basis to optimize traffic, congestion, network growth, and survivability. Conventional optical wavelength-fixed M-XCs usually consist of N sets of 1 × *N* demultiplexers (demuxs) and *N* × 1 multiplexers (muxs) in a back-to-back configuration to allow interchange of wavelength between input and output fibers in a prearranged pattern. In the meanwhile, the wavelength-selective (i.e., rearrangeable) M-XCs can be implemented by adding space-division switches in the configuration.[1] Recently, a dynamic wavelength-selective ADM comprising the reflective fiber Bragg gratings (FBGs) and optical switches (OSWs) was proposed. The system experiments of its add/drop/pass-through functionality's were also reported.[3] In this paper, we present a dynamically wavelength selective M-XC, extending previous concept, using the optical-circulators (OCs) and mechanical-optical-switch (OSW) pairs combined with single or multiple FBG(s) in appropriate connecting paths. Dynamically single- or multi-channel cross-connect can be realized according to the control of the switches and the FBG arrangements.

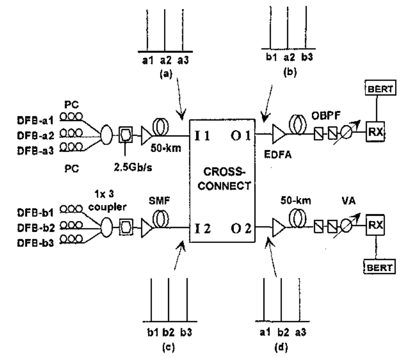
Figure 1 shows the proposed wavelength-selective M-XC. It consists of two three-port optical OCs, two 1 × *N* mechanical OSWs, and *N* pieces of the photoimprinting FBG chains. The center wavelength λ_i of the FBG_i is designed to match the WDM-channel-signal λ_i. For practical operations, the FBG central wavelengths should meet the ITU WDM standardization. Switching the switch-pair to proper position, the desired channel signals can be spatially cross-connected (here, passed through the FBG chain) to another fiber link.



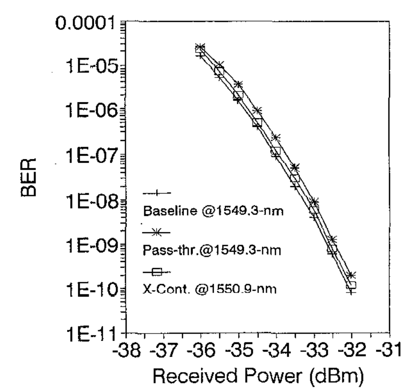
CWT4 **Fig. 1.** Schematic diagram of the (a) conventional and (b) dynamically selective multiwavelength cross-connect switch. OC: optical circulator. FBG: the fiber Bragg grating. OSW: the mechanical optical switch.

In the mean time, other channel signals will be reflected by the FBG chain, then leaving from the port 3 of the OC1, and continuing its forward propagation (here, termed as passed-through) in the same fiber link. When two or more FBGs cascading chain is properly arranged between the switch-pair, multiple channel cross-connection can be realized. Simple 1 × *N* mechanical OSWs can be used for this function with switching time of 0.2–1 ms. There are two input ports I1 and I2, and two output ports O1 and O2 of this M-XC. These two input ports can operate in the same direction or opposite direction, only by re-arranging the three ports of OC2 clockwise or counter-clockwise, dependent on the network structures in which the M-XC located as shown in Fig. 1.

To investigate the feasibility of this M-XC, two sets of multiwavelength transmitters externally modulated at 2.5 Gb/s (see Fig. 2) were used. Each transmitter set comprising three distributed feedback lasers with same wavelength sets of 1547.7 nm, 1549.3 nm, and 1550.9 nm, respectively. The total 100-km transmission link of conventional single-mode fiber (SMF) was arranged. Two erbium-doped fiber amplifiers (EDFAs) were employed to



CWT4 **Fig. 2.** Experimental setup. EDFA: the erbium-doped fiber amplifier, VA: the variable optical attenuator. SMF: the single-mode fiber. PC: the polarization controller. RX: optical receiver. OBPF: optical bandpass filter.



CWT4 **Fig. 3.** The BER performance against the received channel power for the back-to-back (0 km), pass-through (100 km) at 1549.3 nm, and cross-connect (100 km) at 1550.9 nm cases.

provide the required power to compensate the link loss. A narrowband optical bandpass filter (OBPF) was used at the receiving end to select the desired WDM channel for detection. A PINFET receiver with a sensitivity of −32.5 dBm at a BER of 1×10^{-9} was used for the BER performance testing. The averaged cross-connect (reflective- or passed-through path) insertion losses of this M-XC are all about 3.7 dB. The 3-dB passband width and reflectivity of these FBGs are about 0.2 nm and 99%, respectively. All connectors used were physical contact connectors with return loss of <−45 dB.

In our experiment, the optical signal-to-noise ratio were about 62 dB and 45 dB for the passed-through and cross-connected channels due to the filtering-out of the amplified spontaneous emission from EDFA by the narrow, sharp passband of the used FBG. Figure 3 shows the BER performance of the "**a**" set transmitters against the received channel power for the back-to-back (0 km), pass-through (100 km) at 1549.3 nm, and cross-connect (100 km) at 1550.9 nm cases. Note that negligible power penalty of only 0.3 dB was observed in this 2.5 Gb/s × 6 WDM-wavelength network. The system operation and performance confirmed the feasibility of the M-XC. There are several important features for this device with potentially low cross