# A 160-km transparent metro WDM ring network featuring cascaded erbium-doped waveguide amplifiers

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**Abstract:** We demonstrate a 4 x 2.5 Gb/s WDM ring with network-sourced virtual rings comprising optically shared wavelengths. The ring's four nodes feature Erbium-Doped Waveguide Amplifiers (EDWAs), shown here for the first time in cascade, which promise future integrability.

**OCIS Codes:** (060.4510) Optical communication; (060.2320) Fiber optics amplifiers

## 1. Introduction

Recent progress in long-distance optical transmission systems and transparent optical networking support the argument that transparent optical networks will be deployed over significant fractions of the core network [1]. As these technologies mature, it is reasonable to anticipate the adoption of transparent optical networking in the more cost sensitive metro market. One important issue in transparent metro networks is the network operator's ability to control and manage wavelengths injected into the network by users. We demonstrate a four-node, 160-km metropolitan ring network in which all wavelengths are sourced at the network node, obviating the need for user control. Thus, each wavelength, capable of carrying a peak data rate of 2.5 Gb/s, defines a virtual ring network which can be shared among multiple users, who add data with wavelength (and polarization) independent modulators. Fiber and access node losses are offset by four dual-pumped erbium-doped waveguide amplifiers (EDWA).

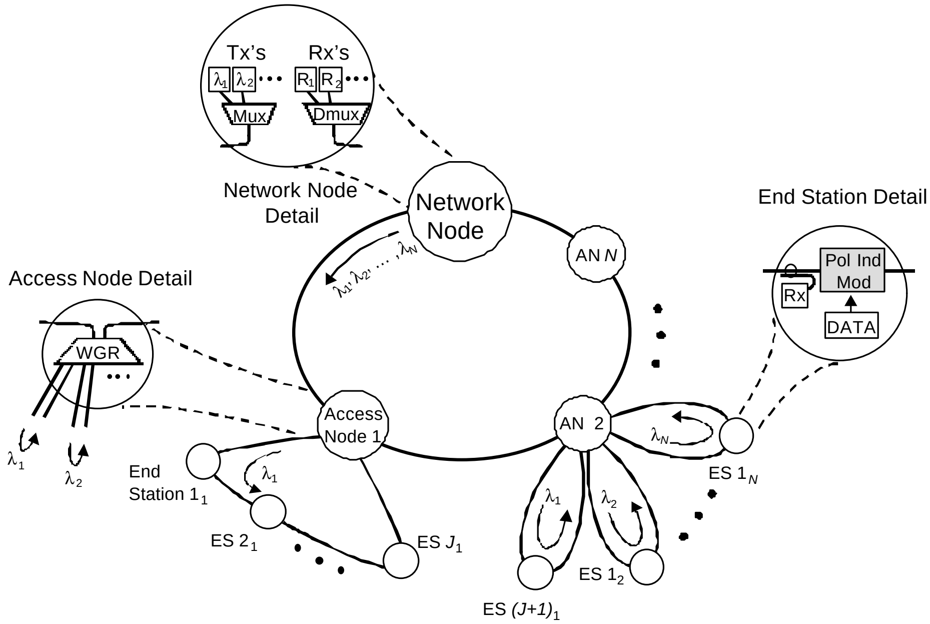

Figure 1: Network concept featuring virtual rings

## 2. Network Concept and Experiment

Figure 1 shows a diagram of the network concept [2]. All N wavelengths are sourced at the Network Node (NN) and are multiplexed onto the ring fiber. An associated set of receivers, also located at the Network Node terminate the ring. Each wavelength can be shared among multiple users over a wide area (as per user

End Station ES $1_1$ through ES $(J+1)_1$, which constitute a virtual ring network on $\lambda_1$) or dedicated to a single user (as per End Stations ES $1_2$ which is served by wavelength $\lambda_2$ off AN 2). A packet protocol, such as FDDI, may be used to share wavelength resources among multiple users. Each Access Node, which consists of a single (2 x2N)-port waveguide-grating router (WGR), drops and re-injects wavelengths onto the ring. Before re-injection, wavelengths may traverse one or more End Stations, where data is received via a 3-dB splitter and receiver (Rx). Upstream packets are created by modulating an incoming “optical chalkboard”, which consists of a string of digital ones transmitted by the NN. As with any metro or access network, the components employed in the user End Stations must be relatively inexpensive. The remote modulators, which are typically tens of kilometers from the laser sources, should be insensitive to both polarization and input wavelength. In a previous two-wavelength, 120-km, three-node ring demonstration [3], semiconductor optical amplifiers (SOA) served as both polarization insensitive 622-Mb/s modulators and in-line amplifiers to overcome transmission losses and excess losses through the Access Nodes. In this paper, we report a four-wavelength, 160-km, four-node ring network, which demonstrates the feasibility of 1) a remote polarization-insensitive semiconductor amplifier/modulator at 2.5 Gb/s and 2) an integrable Access Node consisting of a single planar WGR add/drop in conjunction with a planar erbium-doped waveguide amplifier (EDWA) to offset transmission and excess losses. The experimental configuration is shown in Fig. 2. Four wavelengths, spaced by 100 GHz from 1539.3 nm to 1541.7 nm, are sourced at the Network Node (NN). Three of these wavelengths ($\lambda_1$, $\lambda_3$ and $\lambda_4$) are externally modulated at 2.5 Gb/s by two LiNb0$_3$ modulators with a $2^{31}$-1 PRBS data and inverted data. A 16.5-km spool of conventional fiber, which decorrelates the data on $\lambda_1$ and $\lambda_3$ before launch, is followed by the first of four EDWAs. The remaining wavelength ($\lambda_2$), which is unmodulated at the transmitter, serves as an optical chalkboard for the remote modulator located at either AN 1 or AN 3. The ring nodes are separated by four 40-km spans of conventional fiber. Each Access Node consists of a (2 x 16)-port WGR and an EDWA. The two ports on the “ring side” are connected to the incoming ring fiber and the input to the EDWA, respectively. Pairs of ports on the “users” side are either connected to user End Stations or looped back to create express paths through the AN. Although the WGRs and EDWAs are grown on different substrates (silicon and phosphate glass, respectively), these devices are candidates for hybrid integration into a single compact package.

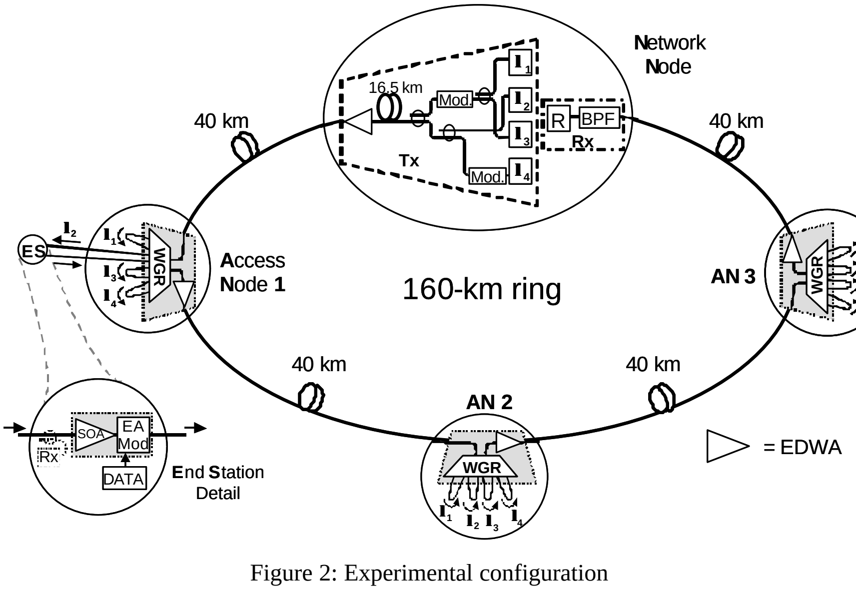

Figure 2: Experimental configuration

The EDWAs are 9.8-cm long buried channel waveguides fabricated with a two-step ion exchange process in Er/Yb-doped phosphate glass [4,5]. Each amplifier is double-pumped with 120-mW co- and counter-propagating pumps at 978 nm and 980 nm, respectively. Differing pump wavelengths are chosen to avoid pump laser interaction through residual pump power. The 978-nm pumps are co-propagating in order to minimize the noise figure, since 978 nm is very close to the absorption peak of Yb. The small signal gain measured at the 1535-nm gain peak is 24 dB. Only the transmitter EDWA is operated well into compression (13-dB gain, 12-dBm total output power). The three AN amplifiers exhibit gains from 17.4 to 20 dB.

A semiconductor optical amplifier (SOA) and an electro-absorption modulator (EAM), serve as the user's remote polarization-independent modulator to add 2.5-Gb/s, $2^{31}$-1 upstream data to $\lambda_2$. (These devices could ultimately be integrated.) The gain contributed by the SOA offsets the excess loss of the EAM and other losses associated with the user ES and its distribution fiber. Setting the net loss seen by $\lambda_2$ to zero, as it loops through the ES and back to the WGR, insures comparable channel powers on the ring (thus permitting the use of passive fiber loop-backs on channels that do not traverse a user at a given AN, such as $\lambda_1$, $\lambda_3$ and $\lambda_4$ in the AN detail in Fig. 2).

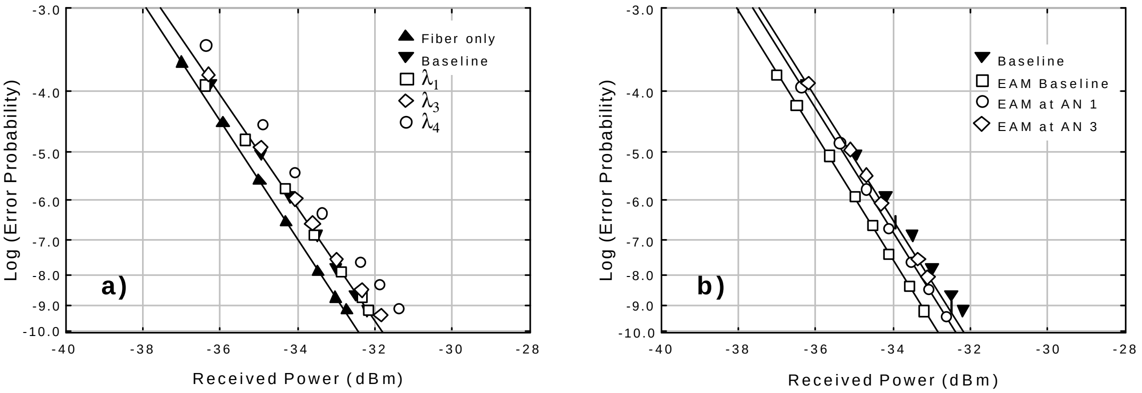

Figure 3: BER performance measurement

Downstream and upstream BER performance measurements are plotted in Fig. 3 a) and b), respectively. The upside-down black triangles in Fig. 3a show the back-to-back baseline performance of the NN receiver. Black triangles show the effect of propagation over the 160-km ring fiber with the ANs bypassed. The 0.8-dB enhancement associated with transmission through the ring fiber is due to chirp imposed on the signal by our single-drive $LiNbO_3$ modulators. The open symbols represent the performance of $\lambda_1$, $\lambda_3$ and $\lambda_4$, (with all channels running) over the entire ring network. The approximate 1-dB power penalty relative to the fiber-only case is attributed to the degradation in optical SNR resulting from the WGR excess losses and the four-EDWA cascade. For clarity, upstream performance of the remote SOA+EA modulator is shown separately in Fig. 3b. Open squares show the back-to-back EA modulator baseline. The $LiNbO_3$ baseline (solid triangles) is shown for reference. The 1-dB sensitivity difference between the EA modulator baseline and the LiNbO3 modulator baseline is attributed to performance differences of the electronic driver circuitry and the BER test sets used in each case. Open diamonds and circles show performance of $\lambda_2$ through the network for the SOA+EA modulator situated at AN 3 and AN 1, respectively. The average power penalty of 0.6 dB does not show a strong dependence (~0.2 dB) on remote modulator location.

## Conclusion

We have demonstrated a 4 x 2.5 Gb/s, four-node 160-km metro WDM ring network. Downstream channels traverse four cascaded EDWAs with less than 1-dB power penalty. Remotely modulated upstream signals exhibit approximately 0.6-dB power penalty. Both the Access Nodes and the user End Stations are configured to benefit from component integration.

## Acknowledgement

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