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A 40 Gb/s DWDM Free Space Optical Transmission Link Over 4.4 km

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Abstract

We simultaneously transmit 16 separate 2.5 Gb/s wavelength data channels, with a 200 Ghz channel spacing, error-free, over a horizontal free space distance of 4.4 km. We believe this result represents the largest bandwidth transmitted at one time over such a distance, without the use of optical transmission fiber.

Keywords: high speed, DWDM, optical wireless

1. Introduction

High-speed free space terrestrial communications links are a complement/alternative to fiber based systems. This is particularly true where geographical limitations and/or installation complexities make fiber installation difficult or cost prohibitive. By leveraging high-speed 1550 nm fiber optics technology with novel optical telescope designs, it now becomes possible to interconnect two locations with "fiber-type" multi-gigabit bandwidths, without any interconnecting fiber. [1,2]

2. Experiment

Figure 1 shows the experimental setup. Sixteen separate wavelength tunable External Cavity Lasers (ECL) sources were used. The ECL laser wavelengths were tuned from 1548.6 to 1573.2, with 200 Ghz (1.6nm) channel spacings. The externally modulated ECL sources were used as a matter of convenience/availability, directly modulated Distributed Feedback (DFB) lasers could have been used just as well. The 16 separate ECL optical signals are combined into subgroups of 4, where each subgroup is then intensity modulated by a Mach-Zehnder $LiNbO_3$ modulator at a data rate of 2.5 Gb/s, i.e. on-off keying. Each intensity modulator is driven by a separate electrical data signal, from a pattern generator. For this experiment, we used a 2^{23} Pseudo Random Bit Sequence (PRBS) bit pattern.

The output of each modulator is amplified by a 1-watt Er-Yb optical amplifier. That is, 4 groups of 4 wavelength channels were simultaneously amplified by each of the four separate 1-watt optical amplifiers. Because of the spectral characteristic of the amplifiers' gain, pre-emphasis of the input signal power levels was necessary to ensure equal output power levels per wavelength channel. The input power levels to each optical amplifier was adjusted, so that all of the output channel powers were the same. Given that the *total* output optical power that this amplifier is capability of producing is 1-watt, the output power levels of each of the 4 amplified signals should be +24 dBm. Figure 2 illustrates the benefit of input signal pre-emphasis.

Figure 2a shows the measured optical spectrum launched into one of the Er-Yb amplifiers. In this example, all four input channels have equal amplitude. The resulting amplified output spectrum is shown

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in figure 2b. This output spectrum clearly shows that the four amplified channels are no longer equal. This signal level imbalance is the result of the optical amplifier gain spectrum not being flat over the wavelength

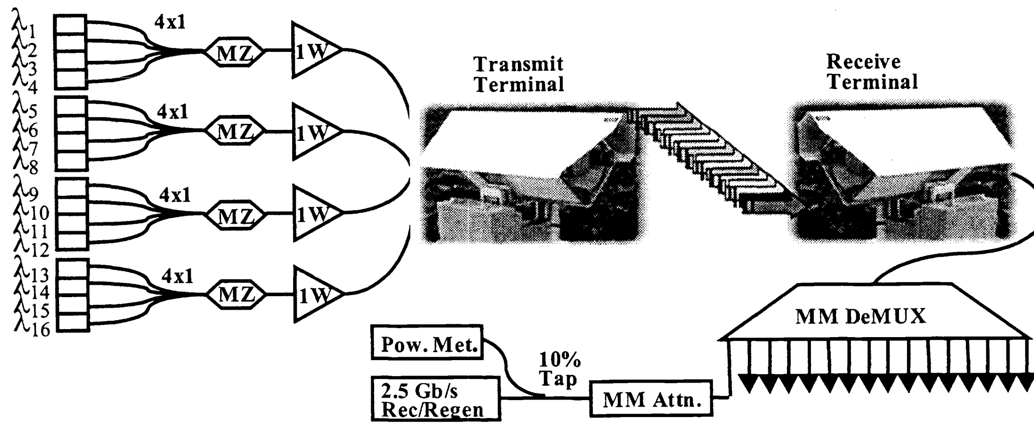

Fig. 1: Experimental Setup

range of the input signals. Figure 2c shows the measured input optical spectrum with pre-emphasis. Figure 2d is the resulting amplified optical spectrum, with the input spectrum as shown in figure 2c. In this case, the amplified signal levels are now all equal. This technique was used to ensure that the power level for each of the 16-wavelength channels sent to the transmitting scope was +24 dBm.

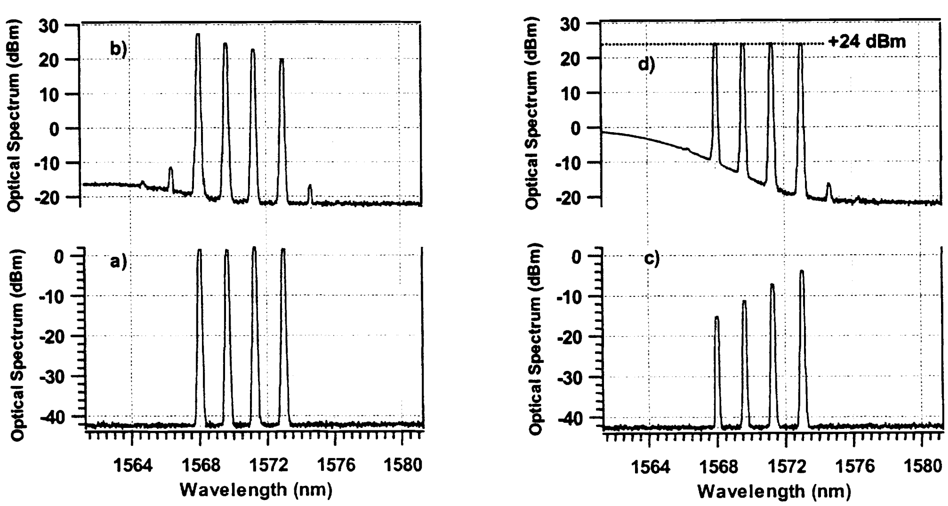

Figure 2: a) Input spectrum to one 1-watt Er-Yb amplifier, equal power per channel, no Input signal pre-emphasis. b) Output spectrum from the same 1-watt amplifier showing uneven gain response. c) Input spectrum to amplifier using pre-emphasis. d) Output spectrum from 1-watt amplifier showing all four channel with equal power levels, +24 dBm.

Another important issue when dealing with multiple optical wavelengths, high power amplifiers and optical fibers, are the effects of optical fiber nonlinearities. Although, the optical signal is transmitted across a free-space horizontal distance of 4.4 km, the signal that is actually transmitted arrives to the transmitting scope through a length of optical fiber. The optical signal originates from a rack of transmission equipment containing ECL lasers, modulators, Er-Yb amplifiers, etc.. The extent and the type of fiber non-linearities encountered depends, among other things, on the;

- spectral characteristics of the optical signal (i.e. modulation format and signal source),
- signal power levels,
- number of different wavelength signals in the fiber,
- wavelength separation between the signals
- fiber type (material and geometrical properties)
- fiber dispersion
- and length of fiber

Fiber non-linearities should be avoided and/or minimized because they degrade system performance [3]. Examples of a few fiber nonlinearities that can be encountered include;

- Stimulated Brillioun Scattering (SBS) which can effectively limit the amount of optical power that can be transmitted down a fiber, causing transmitted power to be reflected back to the source.
- Self-Phase Modulation (SPM) effectively "broadens" the spectrum of the transmitted signal.
- Cross-Phase Modulation (XPM) can occur when two or more wavelength signals co-propagate inside a fiber. The intensity modulation of one channel modulates the phase and hence "broadens" the spectrum of the second channel.
- Four-Wave Mixing (FWM) occurs when two or more wavelengths mix in a nonlinear medium (the fiber) producing optical power at the sum and difference beat frequencies.

In figure 2b, the 1-watt amplifier output spectrum shows some evidence of FWM. In this figure, we see wavelength peaks above and below the four main signal channels. These mixing components are much weaker then the actual signal channels and are therefore no problem. In our transmission experiment, the length of fiber from the 1-watt amplifiers to the transmit scope was about 5 meters.

The output of each of the 1-watt Er-Yb amplifiers is applied to the transmitting telescope. The fiber input to the telescope is a 4x4-fiber coupler, where the coupler output is used to launch four separate propagating beams towards the receiving telescope. Multiple transmit apertures help reduce the effects of atmospheric scintillation (intensity fluctuations) [4]. Additional design and performance details on the transmitter/receiver telescope are described in reference 2.

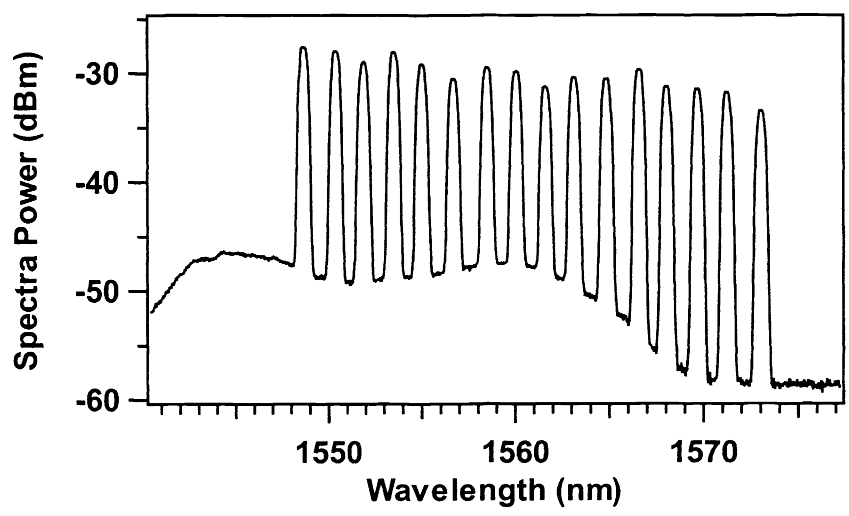

Fig. 3: Received Optical Spectrum

After propagating 4.4km through the atmosphere, the transmitted optical signal was collected by the receiving optical terminal (20 cm receiving aperture diameter) and focused onto a 62.5 μm multimode fiber. Figure 3 shows the received optical signal measured on an optical spectrum analyzer. This measured received optical spectrum clearly shows all 16-wavelength channels. The observed variations in peak channel power can be attributed to scintillation effects and fiber mismatch, i.e. coupling from multimode fiber to single mode fiber. For measurement purposes, the receive multimode fiber was connected to an optical spectrum analyzer, which had a single mode fiber input.

The receiving multimode fiber, which now contains all 16 2.5 Gb/s wavelength channels, was connected to a multimode fiber demultiplexer (MM DeMux). The input fiber and all 16 output fibers for the multimode mode demultiplexer were 62.5 um core-size standard graded index fiber. The measured transmission spectra for the 16-channel MM DeMux is shown in Figure 4. All measurements of the MM DeMux were done with full mode excitation launch conditions. The average insertion loss per channel was less than 3 dB. Channel spacing was 200 GHz, 3dB channel width is 0.8 nm; 20 dB channel width is 1.8 nm. In addition, the adjacent channel crosstalk was 30 dB or better.

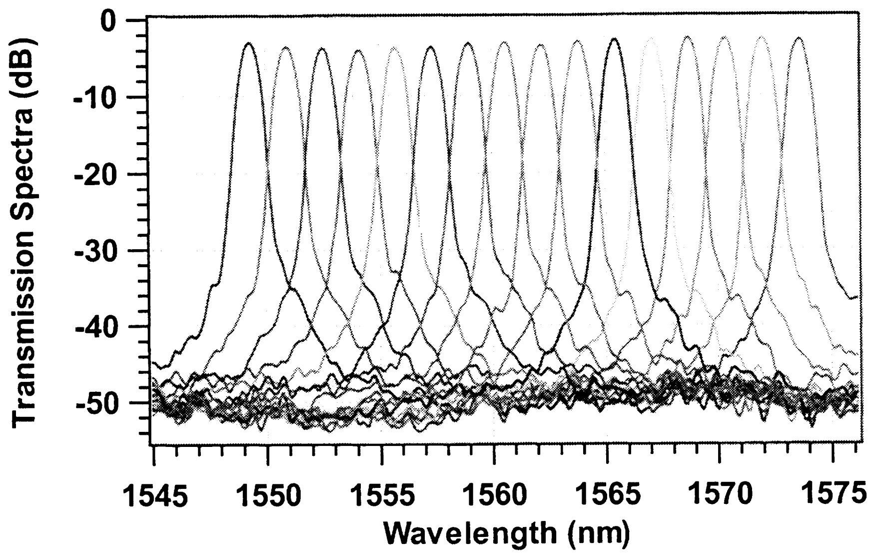

Fig. 4: Multimode DeMux Characteristics

The output fiber associated with a particular dropped channel is connected to a multimode attenuator, which is connected to a multimode 90/10 tap, for simultaneous monitoring the received optical power and Bit Error Rate (BER) performance. The 10% tap output is connected to an optical power meter and the 90% tap output is then applied to a 2.5 Gb/s receiver/regenerator. The regenerated 2.5 Gb/s data and clock signal is then connected to a BER test set error-detector for performance monitoring. The 2.5 Gb/s receiver fiber pigtail is 62.5 μm core size and the receiver sensitivity is about –35 dBm for 10^{-9} BER.

The link performance is monitored by measuring the bit error rate (BER) at consecutive 1-second intervals, i.e., one bit error in a 1-second interval gives a BER of 4×10^{-10}, 2 bit errors gives a BER of 8×10^{-10}, and so on. If there are no recorded bit errors in a 1-second interval, we define that interval error-free and arbitrarily give it a BER of 10^{-12}. This measurement technique permits us to monitor link performance over long periods of time. Figure 5 displays the measured link performance data for each of the 16-transmitted data channels, #1 - #16. Here we see the log(BER) and received optical power (dBm) over a 5-minute measurement period for each channel; that is, each channel was evaluated separately for 5 minutes, one after the other. This data shows that each 2.5Gb/s channel was transmitted error-free for the measurement period. Also, the average received optical power was about –20 dBm per channel, with peak-to-peak fluctuation of as much as 7 dB.

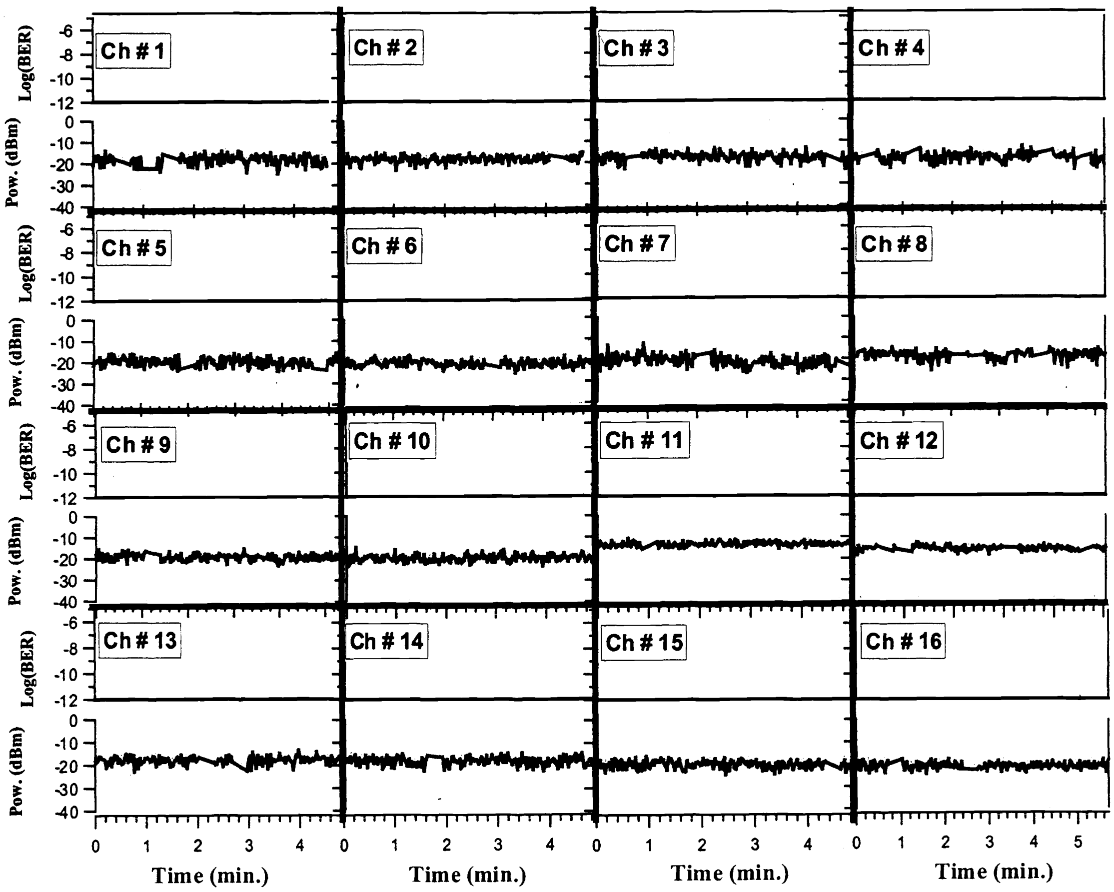

Fig. 5: Link Performance Measurement. Log(BER) and Received Optical Power (dBm) for each of the 16 2.5 Gb/s channels. Each of the 16 sub-graphs represent the measured link performance over a 5-minute period with a 1-second sampling interval.

Conclusions

We have successfully transmitted 40 Gb/s bandwidth, 4.4km through the atmosphere, error-free, by using 1550 nm transmitters/receivers, optical fiber amplifiers, a MM DeMux, and a specially designed optical telescope terminal. These results indicate that multi-gigabit "fiber type" bandwidth can now be achieved through optical wireless transmission.

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