Transmission of 125 WDM channels at 42.7Gbit/s (5 Tbit/s capacity) over 12x100 km of TeraLight™ Ultra fibre

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Abstract: The transmission of 125 ETDM channels at 42.7Gbit/s (5 Tbit/s capacity) is demonstrated over 12x100km of the new TeraLight™ Ultra fibre. The result is obtained with VSB-like filtering at the receiver end and Raman-assisted erbium amplification over C and L bands.

Introduction

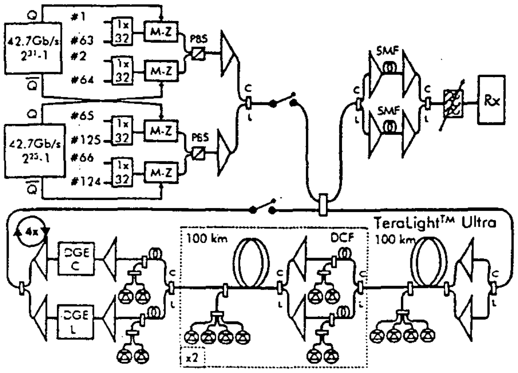
The evolution of multi-terabit/s terrestrial transmission systems has been complying with two trends, either focusing on increasing capacities per fibre in order to save on fibre costs, or on increasing distances in order to save on terminal costs in ultra-long routes. While the 10Tbit/s capacity barrier has been broken recently over limited distances (under 120km) /1//2/, 1200km distance was reached while transmitting data at 3Tbit/s /3/.

Here, we demonstrate 5Tbit/s capacity over 1200km. As in the aforementioned record experiments, our 125 WDM channels carry electrically time-division multiplexed (ETDM) data at 40Gbit/s effective rate. These channels are separated alternatively by 50 and 75GHz and demultiplexed by optical vestigial-side band (VSB) filtering, as proposed in /4/, yielding the high spectral efficiency of 0.64bit/s/Hz with regular NRZ format. The transmission is carried out over twelve 100km-long spans of the new TeraLight™ Ultra fibre, separated by Raman-assisted erbium-doped fibre amplifiers (EDFAs) operated in C and L bands.

Experimental set-up

Figure 1 shows the set-up of the recirculating loop. The WDM transmitter consists of 125 DFB lasers with wavelengths ranging from 1529.94nm to 1561.22nm in the C-band and 1571.03nm to 1602.53nm in the L-band. In each band, two sets of 125GHz-spaced channels, shifted with respect to each other by 50GHz and corresponding to odd and even channels respectively, are combined through 1x32 array-waveguide multiplexers. They are modulated independently by two Mach-Zehnder modulators (M-Z) fed by a 2^{31}-1 pseudo-random bit sequence (PRBS) for the set including the channel under test and a 2^{23}-1 PRBS for the other set. Both PRBS are generated electrically, out of two separate pattern generators. Such a scheme provides effective decorrelation of the data carried by neighbouring WDM channels. Each generator delivers four sequences at 10Gbit/s with 7% overhead, i.e. at 10.7Gbit/s, to emulate the presence of forward error correction (FEC). The sequences are combined through Si-Ge-based 2:1 MUX circuits for successive 10.7:21.3Gbit/s and 21.3:42.7Gbit/s electrical multiplexing. The resulting complementary outputs at 42.7Gbit/s, forming real PRBS patterns, are amplified in order to drive the M-Zs. Odd and even modulated channels are interleaved with orthogonal polarisations through polarisation beam splitters (PBS), boosted, passed into an acousto-optic switch and sent into the loop via a 3dB coupler.

Figure 1: Experimental set-up

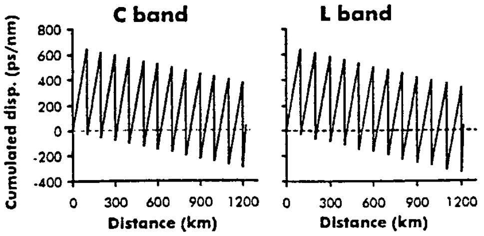


The loop consists of three 100km-long sections of TeraLight™ Ultra fibre. This non-zero dispersion-shifted fibre complies with all the characteristics of TeraLight™ fibre /4/, with a chromatic dispersion of 8ps/nm.km, loss of 0.20dB/km and effective area of 63µm² at 1.55µm. However, the tighter specifications on PMD (total 1ps per loop round-trip), dispersion slope (0.052ps/nm².km) and the guaranteed low loss within the wavelength region of Raman pumps (0.25dB/km at 1.45µm) make it particularly suited for transmissions over ultra-long haul distances.

Two sections of dispersion compensating fibre (DCF) for C and L bands are inserted within each repeater. They provide full dispersion slope compensation, so that the excursion of cumulated dispersion does not exceed 10ps/nm per fibre span along the whole multiplex. The corresponding dispersion maps are represented in Fig. 2 at 1545nm and 1585nm. These maps were optimised based on computer simulations, and further verified experimentally. Fine tuning of the residual dispersion is performed on channel-by-channel basis by including a small spool of standard single-mode fibre (SMF) within the receiver preamplifier, outside the loop.

Each span is separated by repeaters formed of dual-band EDFAs providing a total 18dBm and 16dBm in C and L-band, respectively. In each of them, EDF length was carefully adjusted to deliver higher gain (2dB in C-band, 1dB in L-band) in the lower-wavelength region than in the higher-wavelength one, so as to mitigate self-induced Stimulated Raman scattering (SRS) spectral distortions /5/.

Figure 2: Dispersion maps

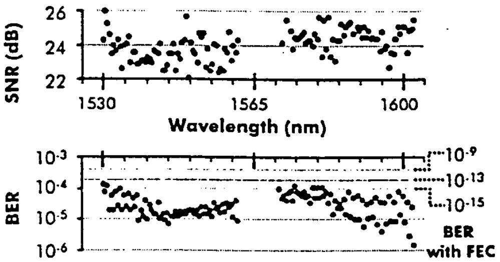


Moreover, in order to improve the overall signal-to-noise ratio (SNR), four sets of two polarisation-multiplexed semiconductor pumps, of respective wavelengths 1427nm, 1439nm, 1450nm and 1485nm, are sent backwards into the transmission fiber in order to provide extra amplification through SRS. Similarly, four laser pumps, two in both bands, are sent into the DCFs in order to mask DCF loss and thus improve the noise figure of the EDFAs. These pumps are at wavelengths 1423nm and 1455nm for the C band and 1470nm and 1500nm for the L band. Raman gain is approximately 15dB and 8dB in the TeraLight™ Ultra and in the DCFs respectively. Note that the last repeater consists of dual-stage EDFAs which incorporate dynamic gain equalisers (DGE) to ensure optimal gain flatness in both bands. Power excursion after 1200km is better than 3dB, as depicted in the spectrum of Fig. 3. Another acousto-optical switch closes the loop. Like the first switch, it is driven by electrical delay generators which trigger the periodical filling and clearing of the loop, synchronously with the measuring equipment.

In the receiver, each channel is selected with a very narrow (30GHz at 3dB), tuneable filter. This filter performs VSB filtering when tuned off the channel central frequency towards the 75GHz-spaced neighbouring channel. Thus, only the side-band experiencing the smallest overlap with adjacent channels is isolated regardless the crosstalk affecting the other side-band /4/. An EDFA boosts the VSB signal to 12dBm on the pin-photodiode

Figure 4 represents the experimental results at 1200km, after 4 round-trips in the loop. The optical SNR at the input of the receiver preamplifier in a 0.1nm bandwidth varies within [22.1dB, 26.0dB] and [22.7dB, 27.6dB] in C-band and L-band, respectively. The BERs of all 125 channels are also shown. Note that in our ETDM receiver, the 42.7-to-10.7Gbit/s demultiplexer uses a phase-locked loop which is automatically reset at each round-trip of the recirculating loop. This randomly changes the measured 10.7Gbit/s tributary and ensures that the BER performance of Fig. 4 exactly represents the average performance of all four 10.7Gbit/s tributaries. Measured BERs are always better than $1.4.10^{-4}$. With FEC, this would correspond to a BER performance lower than 10^{-13}. Note that the worst performing channels were found mainly limited by optical non-linearities, as testified by their relatively larger SNR.

Figure 4: Experimental results



Conclusion

We have transmitted data at 5Tbit/s over twelve 100 km-long spans of TeraLight™ Ultra fibre, yielding 6Pbit/s.km capacity times distance product. This was obtained by sending 125 WDM channels modulated at 42.7Gbit/s and alternatively spaced by 50/75 GHz into a loop including Raman-assisted C and L band EDFAs. VSB filtering was applied at the receiver end.

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Figure 3: Optical spectrum after 1200km (0.1nm resolution)