ENHANCING THE PERFORMANCE OF DIRECTLY-MODULATED LASER SYSTEMS USING NEGATIVE DISPERSION FIBER FOR METRO APPLICATIONS

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Abstract:

Single channel OC-48 transmission over 600 km and 32 channel OC-48 transmission over 300 km using directly modulated DFB lasers operating over a prototype negative dispersion fiber *without any* dispersion compensation is reported. The use of a negative dispersion fiber greatly enhances the transmission performance of directly modulated lasers compared with positive dispersion fiber.

Introduction

Recently, in order to satisfy the growing demand for bandwidth in the access network, there has been increased interest in low-cost DWDM systems for use in metropolitan area networks. Such systems differ from long-haul DWDM systems in that they are far more sensitive to terminal equipment costs, requiring the use of low-cost components such as directly-modulated DFB lasers. Transparent optical reconfigurability using Wavelength Selective Cross Connects (WSXC) and Wavelength Add Drop Multiplexers (WADM) offer potentially lower costs by eliminating unnecessary O/E/O conversion in such networks. However, O/E/O conversion also carries out useful signal regeneration for paths that would otherwise be limited by the build up of impairments. In low cost metro DWDM systems using Directly Modulated Lasers (DMLs) and positive dispersion fiber such as standard single-mode fiber, dispersion is the main impairment that limits the unregenerated signal reach. The use of Dispersion Compensating Fiber (DCF) to extend the reach would be cost prohibitive for metro systems and the placement of the DCF becomes an issue in network topologies where different optical channels in a fiber originate from different nodes and hence see different amounts of accumulated dispersion. In addition, the increased loss of the DCF would negatively impact system performance.

The use of a Non-Zero Dispersion-Shifted Fiber (NZ-DSF) is a far more attractive solution for greatly enhancing the dispersion-limited transmission distance. However, the need to maintain low and non-zero dispersion over the entire usable bandwidth (1280 to 1620 nm) means that a mere reduction in the dispersion alone would not be sufficient to significantly enhance the dispersion limited distance.

We show that by making the fiber dispersion negative all the way through to the edge of the L-band (1620 nm), we can take advantage of the positive chirp characteristics of directly modulated lasers to enhance signal transmission. In this paper we demonstrate through experimentation and corroborative simulation that the performance of directly modulated lasers can be greatly enhanced by transmission over negative dispersion fiber compared with positive dispersion fiber. Hence, be employing a fiber with both low and negative dispersion, the uncompensated transmission distance can be maximized. Such a fiber is used to demonstrate single channel OC-48 transmission over 600 km and 32 channel OC-48 transmission over 300 km using directly modulated DFB lasers *without any* dispersion compensation.

By facilitating signal transmission well beyond the conventional 80 km to 100 km dispersion limit of directly modulated lasers, this fiber could act as a key enabler for low-cost transparent optical networking in the metro area.

Experimental comparison of positive and negative dispersion tolerance

In order to compare the tolerance of directly modulated DFB lasers to positive and negative dispersion, we measured the performance of different DFB lasers over positive dispersion using standard single mode fiber (SSMF) fiber and over negative dispersion using Dispersion Compensating Fiber (DCF). The lasers were modulated at 2.5 Gbps with a 2^{31}-1 pseudo random bit sequence. EDFAs were used to compensate for the fiber losses (NF = 6 - 7 dB). Variable Optical Attenuators (VOAs) were placed before and after each amplifier to set the optical signal power level launched into each fiber span to 0 dBm and the input signal power level into each EDFA to –26 dBm. An optically pre-amplified receiver was used to detect the optical signal after propagation through the fiber.

In all, a total of five different commercially-available DFB lasers from three different vendors were measured. The lasers had rated dispersion tolerances for +D fiber between 1440 ps/nm and 3000 ps/nm for OC-48 transmission. All lasers had the same nominal wavelength of 1544 nm.

The receiver sensitivity and Q-factor for each of the five lasers are plotted as a function of dispersion in Figure 1. The results are plotted at three of four different extinction ratios for each laser. The receiver sensitivities were measured at a BER of 10^{-9}. Lasers 2 to 5 show substantially greater tolerance to negative dispersion than to positive dispersion. This performance enhancement is dependent upon the extinction ratio, with the lasers performing better at lower extinction ratios. Laser 1, however, showed no significant difference between performance over positive of negative dispersion fiber. A time-resolved chirp measurement of each revealed that Laser 1 was adiabatic chirp dominated, while Lasers 2 to 5 were transient chirp dominated. The effect of this difference will be described in more detail later on in the paper.

The maximum dispersion tolerance for each of the five lasers is shown below in Table 1. Here, the dispersion tolerance is defined as the maximum dispersion for which Q > 9 dB (i.e. BER<10^{-15}). The extinction ratio at which this is achieved is also shown. If we limit ourselves to extinction ratios of more than 8.2 dB, as specified in current SONET/SDH specifications [1], [2], the dispersion tolerances achieved are shown in Table 2.

Note that improvements in absolute dispersion tolerance of typically 100% were observed under optimized bias conditions, and improvements of about 50% were observed under standard SONET drive conditions, by using a negative dispersion fiber.

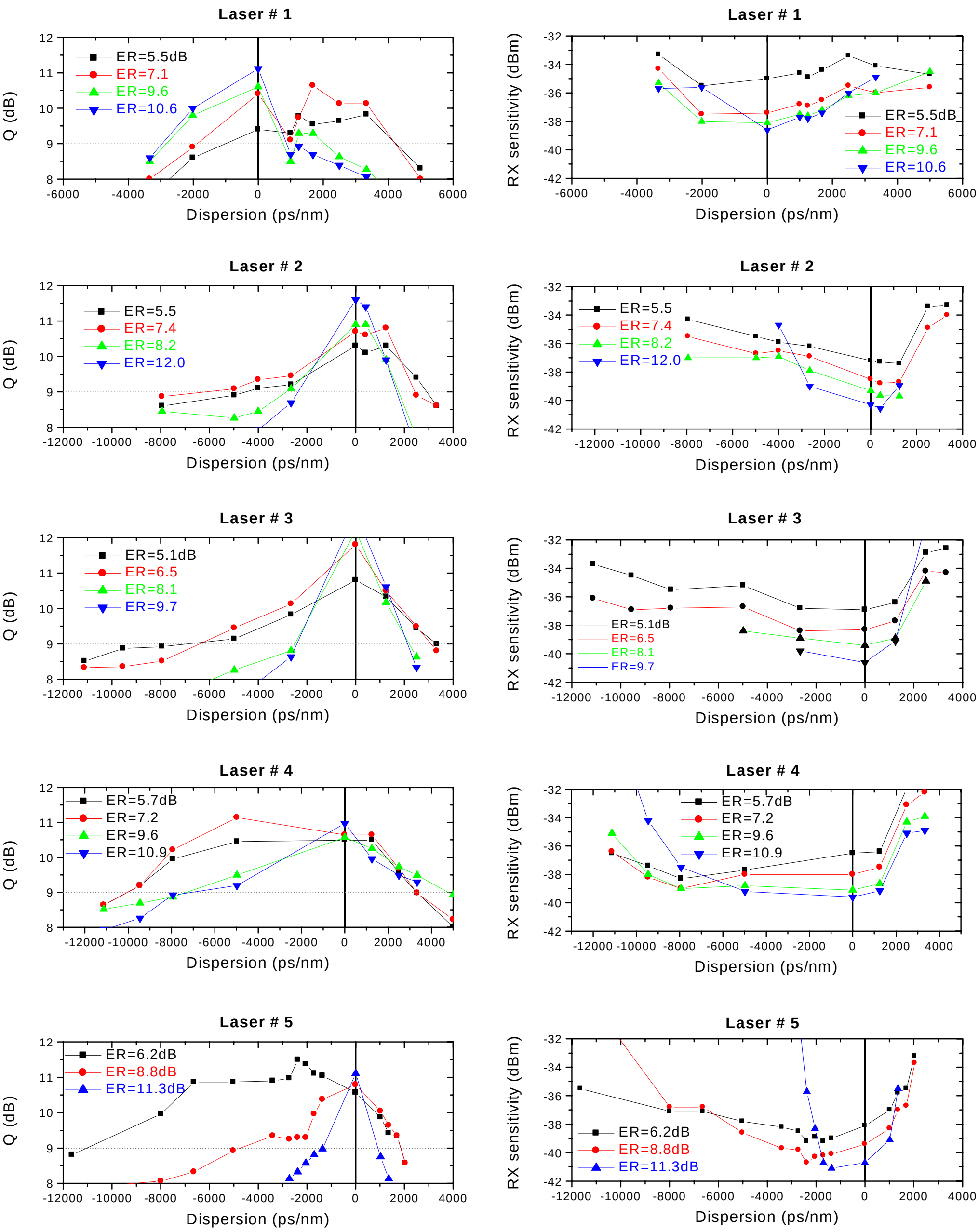

Figure 1. Transmission performance of directly modulated lasers over positive and negative dispersion fibers.

Laser #	Positive Dispersion Tolerance	Negative Dispersion Tolerance	Percent improvement in absolute dispersion tolerance for negative dispersion
1	+4200ps/nm @ ER=7.1dB	-3000ps/nm @ ER=10.6dB	-28%
2	+2900ps/nm @ ER=5.5dB	-6200ps/nm @ ER=7.4dB	114%
3	+3400ps/nm @ ER=5.1dB	-7000ps/nm @ ER=5.1dB	106%
4	+4800ps/nm @ ER=9.6dB	-10000ps/nm @ ER=7.2dB	108%
5	+1800ps/nm @ ER=8.8dB	-11000ps/nm @ ER=6.2dB	511%

Table 1 . Dispersion tolerance of DMLs at optimized extinction ratios.

Laser #	Positive Dispersion Tolerance	Negative Dispersion Tolerance	Percent improvement in absolute dispersion tolerance for negative dispersion
1	+2100ps/nm	-3000ps/nm	43%
2	+1700ps/nm	-2600ps/nm	53%
3	+2200ps/nm	-2500ps/nm	14%
4	+4800ps/nm	-7300ps/nm	52%
5	+1800ps/nm	-4700ps/nm	161%

Table 2. Dispersion tolerance of DMLs under SDH/SONET specified extinction ratios of >8.2dB.

Performance over 600 km of a prototype negative dispersion fiber

A similar laboratory test was performed using prototype fiber having λ_0 near 1630 nm and a slope typical of other NZ-DSF fibers. As shown in Fig. 3, error-free transmission (BER<10^{-15}) over the 600 km of the prototype negative dispersion fiber with 6 in-line amplifiers could be obtained using a DM-DFB laser rated for 80 km of transmission distance over standard single mode fiber (SSMF). Again, this result was achieved with no additional dispersion compensation in the system. This shows that a significant increase in propagation distance is possible when negative dispersion fiber is used in combination with less expensive DM-DFBs expected to be used in metropolitan systems.

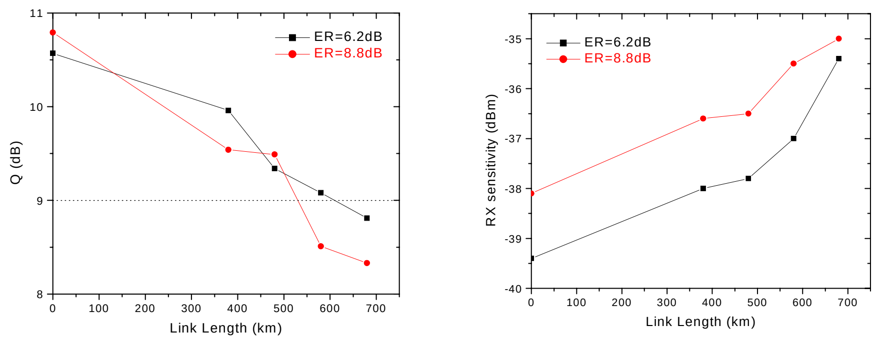

Figure 2. Measured performance of Laser 5 over 600 km of a prototype negative dispersion fiber.

32 channel, 300km DWDM transmission experiment

MetroCor™ fiber is a negative dispersion fiber with a zero dispersion wavelength beyond the L-band, and a dispersion slope typical of other NZ-DSF fibers. MetroCor fiber, which has negative dispersion throughout the entire usable bandwidth (1260 – 1620 nm), can be used to enhance the transmission performance of DM-DFB lasers. The fiber used in experiment had an average dispersion of about -3 ps/nm/km in the L-band and about -8 ps/nm/km in the C-band.

A 32-channel DWDM transmission experiment was conducted to verify the performance of MetroCor in a typical medium haul DWDM transmission link. The channels are between 1533.5 nm and 1558.2 nm with 100 GHz spacing. Each laser was modulated with at 2.5Gbps with an extinction ratio of more that 8.2 dB.

Figure 3 shows the comparison of the Q-factors after propagating through 300 km of MetroCor (Negative Dispersion Fiber (NDF)) and 300 km of standard single mode fiber (SSMF). As shown by the solid dots, all 32 channels have a Q higher than 9 dB, corresponding to a bit error rate (BER) lower than 10^{-15}, after transmitting over 300 km of MetroCor. In contrast, all of the channels fail after propagating 300 km over SSMFs, as shown by the open circles. Obviously, the performance difference between MetroCor and SSMF is strongly device dependent, as shown by the Q variations of the same channel over two types of fibers.

The power penalty for achieving a BER of 10^{-10} was also measured. After 300 km of MetroCor, all 32 channels need less power than their back-to-back case for achieving the specified BER. The "negative power penalty" or performance enhancement ranges from 0.3 dB to about 1.5 dB. On the other hand, there is a large power penalty ranging from 4 dB to over 10 dB for these signals to propagate through 300 km of SSMF.

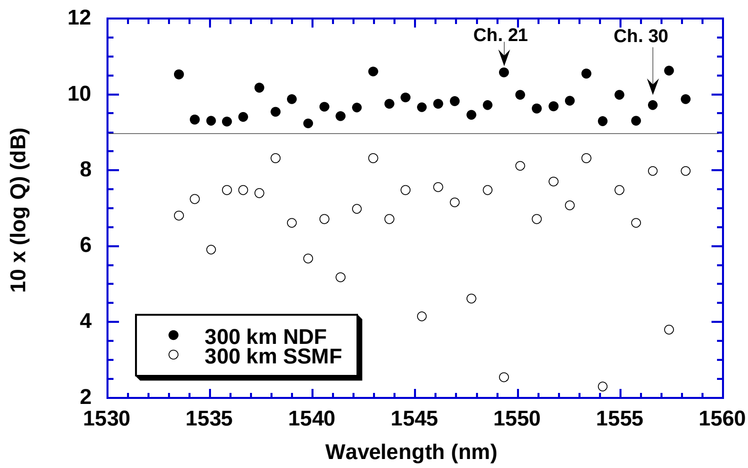

Figure 3. Q-factor comparison of 32 DMLs over 300 km of MetroCor (Negative Dispersion Fiber - NDF) and standard single mode fiber (SSMF).

In order to characterize the different transmission performance of lasers across the channel plan, the power and chirp waveforms at the output of the DMLs were measured (Figure 4 shows the results for ch.21 and ch.30). Clearly, the DML of ch.21 is transient chirp dominated while the one of ch.30 is adiabatic chirp dominated [6].

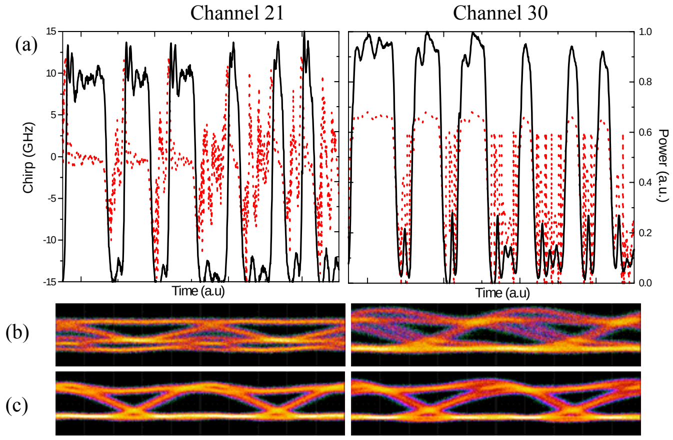

Figure 4. (a) Power (solid line) and chirp (dotted line) waveforms for ch. 21 and ch. 30. The received eye-patterns at the receiver are also shown for transmission over 300 km of (b) SSMF and (c) MetroCor.

In the case of ch.21, the blue shifted leading edge of the pulses advances relative to the main portion of the pulses for transmission over positive dispersion fiber (SSMF). This results in intersymbol interference and the eye in this case will be severely closed Figure 4(b). On the other hand, the chirped leading edge will compress the pulses through transmission over MetroCor and the eye will look perfectly open Figure 4(c). In the case of ch.30 where the transient chirp has been completely "masked" by the adiabatic chirp, the shape of the received eyes can be described by considering the "self-steepening" effect [3]. In this case, the transmission performance is determined mainly by the absolute value of dispersion and not its sign. The eye corresponding to SSMF is more distorted than that of MetroCor mainly because of the larger absolute value of the dispersion. The different dispersion sign will affect the symmetry characteristics of the eye.

The above considerations are qualitatively confirmed by simulation. The DFB semiconductor laser is modeled by rate equations [4]. The seven most influential parameters of the DFB laser are varied around the values given by [5] as shown in Table 3. Each range is sampled at the end points and the middle, yielding a population of 2,187 lasers. Thermal effects and laser parasitics are ignored.

Symbol	Units	Description	Range
tc	ns	Carrier lifetime	0.5-3.5
V	e-17 m^3	Active volume	2.0-10.0
a0xvg	e-12 m^3/s	Differential gainxgroup velocity	1.0-9.0
n0	e24 1/m^3	Carrier density at transparency	0.5-2.5
L	mm	Length	0.2-0.4
ε	e-23 m^3	Nonlinear gain compression factor	1.0-9.0
α		Linewidth enhancement factor	3.0-9.0

Table 3. Most influential DFB laser parameters

The modulating current is composed of 2.5 Gb/s raised-cosine current pulses with rise and fall times of 100 ps. Bias currents for the ones and zeros are chosen to achieve 1mW average optical power and 10 dB extinction ratio for each laser. Under these driving conditions, 11% of the generated laser population present power ringing that causes more than 1 dB eye closure back-to-back and they are rejected from the population. The rest of the laser waveforms are transmitted through the fiber.

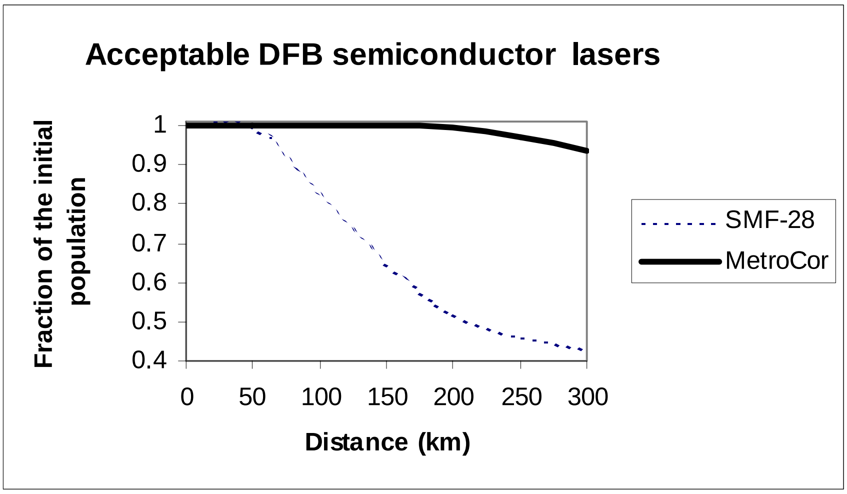

Figure 5. **Simulated yield for DMLs to propagate through MetroCor (NDF) and SSMF, at the wavelength of 1528.77 nm. For C and L band operation, this wavelength corresponds to the worst case for MetroCor fiber, where the dispersion is maximum, and the best case wavelength for SSMF, where the dispersion is minimum. Even in this worst case, the vast majority of simulated DFB lasers work well with for 300 km of MetroCor fiber.**

The fiber is modeled as an all-pass filter with quadratic phase [7]. Non-linear effects are ignored due to the small transmitted powers and the short distances in typical metropolitan networks. The receiver optical filter is assumed third-order Butterworth filter. The photodiode is modeled as a square law detector followed by a 4-th order Bessel electric lowpass filter. The chirp-induced penalty is estimated by calculating the amount of eye degradation at the output of the receiver [7].

Lasers exhibiting more than 2-dB dispersion induced penalty on SMF-28 for a dispersion parameter-length product DL<1000 ps/nm are rejected from the laser population. This additional rejection criterion helps to eliminate samples that are not representative of commercially available devices (which in general have a dispersion budget DL>1200 ps/nm)..

Figure 5 shows the fraction of the initial acceptable laser population that has less than 2-dB dispersion induced penalty as a function of distance. The transmission wavelength is chosen to be 1528.77 nm, which is at the lowest end of the C-band. For C and L band operation, this wavelength corresponds to the worst case for MetroCor fiber, where the MetroCor fiber has its maximum dispersion. Conversely, 1528.77 nm is the best case for SSMF, since the fiber dispersion is at the minimum value. The solid line corresponds to MetroCor fiber and the broken line to SSMF. Even for this worst case wavelength, at least 94% of the lasers can go through 300 km of MetroCor fiber. A significantly higher fraction of DFB lasers covering the entire C and L bands would For wavelengths in the mid to upper portion where at most 43% of the remaining lasers can go through 300 km of SSMF. These numbers are based on the assumption that the probability of occurrence of each DFB semiconductor laser in the simulated population is the same.

Operation in the 1310nm window

Performance of a negative dispersion fiber in the 1310 nm window could be a concern [7]. Testing was carried out over up to 60 km of the prototype negative dispersion fiber using five uncooled directly-modulated 1310 nm lasers operating at 2.5 Gbps. Error-free performance was achieved with all devices up to 60 km, at which point transmission was loss limited. For 40 km transmission the devices showed negative power penalties of between 0.5 dB to 1 dB. Hence, this fiber design is functional over shorter metropolitan distances where 1310 nm lasers may remain in use.

Summary and conclusions

We have shown that negative dispersion fiber enables greatly enhanced dispersion performance of directly modulated DWDM laser systems. The exact magnitude of the performance improvement is dependent upon the laser chirp characteristics. We fabricated a prototype negative dispersion fiber that has negative dispersion over the entire C- and L-bands, and using this fiber, demonstrated 2.5 Gbps single channel transmission using a directly modulated laser over 600 km and the transmission of 32 OC-48 channels (100 GHz spaced) over 300 km. Such fiber is deemed to be an enabler for low-cost transparent optical networking in the metro area.

References

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