SHORT PULSE LASER SOURCES FOR OPTICAL TIME DOMAIN MULTIPLEXING

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1. INTRODUCTION

One of the main goals in optical communication research consists in enlarging the transmission capacity of the established optical links. But provided that changing the currently installed fiber optic cables involves huge expenses, efforts are concentrated on increasing the capacity of these cables by means of multiplexing techniques.

Just as in electrical communications, there are two basic methods for optical multiplexing, namely frequency and time division multiplexing. Frequency multiplexing in the optical range is commonly known as Wavelength Division Multiplexing (WDM) and it consists in launching several lasers of different wavelength into the same fiber, each of them modulated according to a different electrical signal. On the other hand, Optical Time Division Multiplexing (OTDM) combines several lasers of the same wavelength using a pulse modulation with Return to Zero (RZ) for each and introducing proper delays between the pulses to avoid time overlap, interleaving the pulses in a time slot.

Each of these techniques alone can give very high transmission rates in the order of the tens or hundreds of gigabits per second. Furthermore, both multiplexing methods are compatible and experiments have been made where their combined use has achieved transmission rates in the order of terabits per second, showing the amazing possibilities for future development in this field.

For further reference about multiplexing in optical communication systems see:

- SPIRIT, D.M. and O'MAHONY, M.J.: *High Capacity Optical Transmission Explained.* Wiley, 1995.
- AGRAWAL, G.P.: *Fiber-Optic Communication Systems.* Wiley, 1997.
- SENIOR, J.M.: *Optical Fiber Communications.* Prentice-Hall, 1985.

2. OUTLINE

The authors of this article were working for two weeks at the Department of Electromagnetic Systems of the Danish Technical University (DTU) under the supervision of Henrik Poulsen, Anders Clausen and Alvaro Buxens, in the context of a summer course organized by the Board of European Students of Technology (BEST) in August 1998. Our main objective was the creation of short laser pulses for OTDM applications. The shorter the pulses, the larger the number of them which can be multiplexed in a given period of time and therefore the higher the transmission rate, fixed the information contained in each pulse (one bit for the usual two-level transmission).

Our experimental work developed according to the following steps:

- Characterization of the distributed feedback (DFB) laser diode.
- Pulse compression.
- Transmission over Dispersion Shifted Fiber (DSF) and Standard Single-Mode Fiber (SSMF).
- Multiplexing of pulses for OTDM transmission.

3. CHARACTERIZATION OF DFB LASER DIODE

We worked with a new DFB laser diode manufactured by France Telecom/CNET model 668.5/4G2 with a nominal wavelength of 1551.3 nm at 25°C and a physical length of 160 μm.

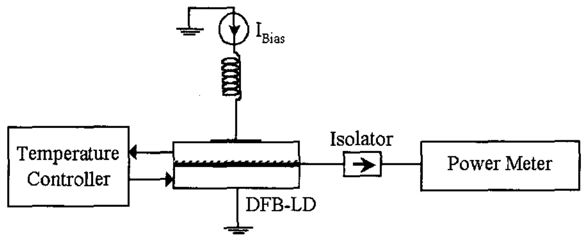

Figure 1. Experimental setup for static characterization.

The first step was a static characterization of the laser, studying its behaviour under continuous bias current obtaining a CW light, using the experimental setup shown in figure 1.

We mesured the optical power at the output of the laser for different values of the bias current at the input (figure 2a). We saw that the output power begins increasing when the bias current surpasses the threshold at about 4 mA.

We also studied the changes in the laser wavelength under temperature variation (figure 2b): we observed a linear dependency between both magnitudes that allowed a tuning range of about 0.9 nm for temperatures from 20 to 30°C. We choose a working temperature of 20°C that gave us an output wavelength of 1550.9 nm.

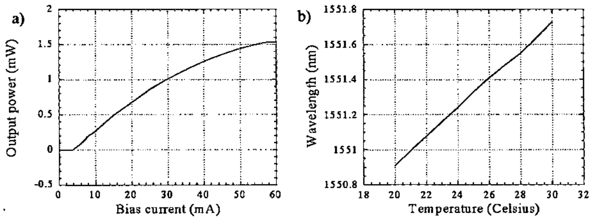

Figure 2. a) Output power versus bias current. b) Output wavelength versus temperature.

The next step consisted in adding a 10 GHz sinusoidal signal to the bias current at the laser input and studying the optical output by means of a 32 GHz photodiode connected to a 40 GHz sampling oscilloscope (figure 3).

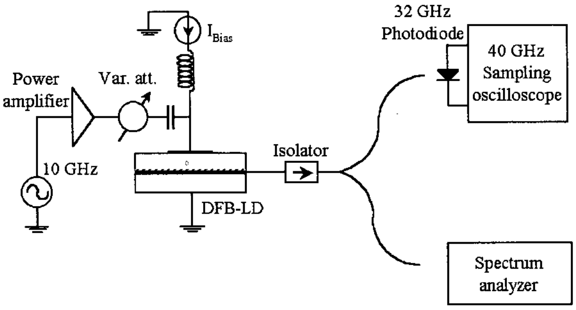

Figure 3. Experimental setup for dynamic characterization.

In this way we obtained an amplitude modulation in the laser. However, because of the non-linear response of this device, the output showed a pulsed rather than sinusoidal profile, as seen figure 4.

We minimized the pulse width using the optimum relation between the amplitude of the modulator signal and the bias current. After doing this we obtained pulses with a Full Width Half Maximum (FWHM) of 23.4 ps.

Here we observed for the first time a side effect that would be the key for our further experiments. When modulated in amplitude, a laser diode undergoes small changes in carrier density, which alter the refractive index of the resonant cavity and so the laser wavelength. Hence, the amplitude modulation of the laser involves also an optical frequency modulation, commonly known as chirp.

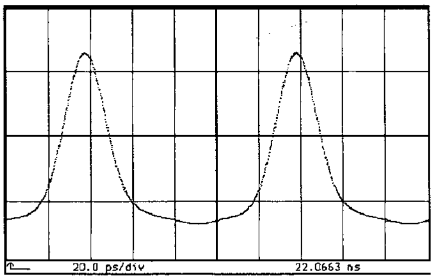

Figure 4. Output optical signal (FWHM=23.4 ps)

As the frequency shift was too fast for the spectrum analyzer to detect, what we saw on the screen was only a broadening of the peak around the central carrier frequency (figure 5).

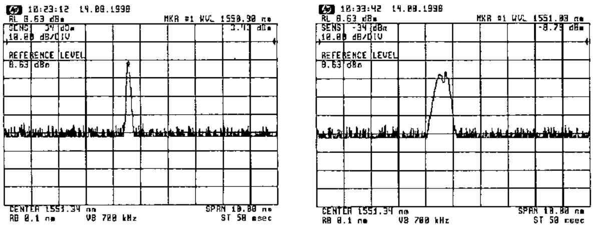

Figure 5. Laser spectrum before and after modulation.

4. PULSE COMPRESSION

Our next goal was to reduce the width of the output pulses, and we did it taking advantage of their chirp. Because of this effect, the laser wavelength at the beginning of the pulse (positive slope) is shorter than at the end (negative slope). Therefore, if we inject the pulse into a fiber which propagates long wavelengths faster than short, both slopes will get closer and the pulses will be narrower. As figure 6 shows, this behaviour of the group delay (t) corresponds to negative dispersion (D) fibers, that is, optical fibers with dispersion less than 0 ps/nm/km at the usual working wavelength of ~1550 nm.

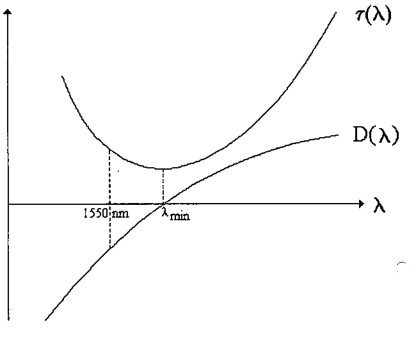

Figure 6. Dispersion and group delay in a compression fiber.

We had to find the proper value for the dispersion of the compression fiber, since an excess in its absolute value would have resulted in the short wavelength advancing the long ones and broadening the pulses again. After trying different fibers we chose one with a dispersion of -21.6 ps/nm, which gave pulses with a FWHM of 17.67 ps (figure 7). So, we achieved a compression of more than 6 ps, as well as a significant increase in extinction ratio (power difference between the peak and the base of each pulse).

However, mesurement of such narrow pulses cannot be very accurate when taken with a 40 GHz oscilloscope using a 32 GHz photodiode. So, we substituted the scope by a streak camera, which is a CCD-based liquid-cooled device connected to a computer, which allows more precise mesurements. According to them, our pulses had in fact a FWHM of only 10 ps (figure 8).

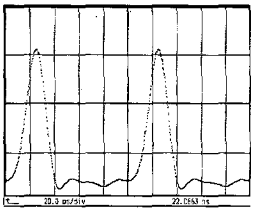

Figure 7. Output signal after compression (FWHM=17.67 ps).

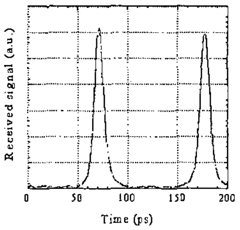

Figure 8. Compressed pulses mesured with the streak camera (FWHM=10 ps).

5. PULSE TRANSMISSION

Initially, we transmitted over Dispersion Shifted Fiber (DSF), which is fiber with its zero dispersion wavelength around 1550 nm. This allowed us to transmit over 22 km of fiber without observing any significant pulse broadening. This indicates that much longer distances are possible, and this has also been experimentally verified.

This was repeated with Standard Single-Mode Fiber (SSMF), which the vast majority of the already installed fiber infrastructure is based on. Standard fibers have the zero dispersion wavelength around 1300 nm, and therefore they have a large positive dispersion at 1550 nm (figure 9), and as a result the pulse width increases quickly during transmission.

After transmitting over 4 km of SSMF, our 17.67 ps wide pulses broadened until reaching a FWHM of 64.8 ps (figure 10a). However, we can compensate this effect of the SSMF by connecting it to a fiber with opposite dispersion, that is, a negative dispersion fiber (figure 6), usually called Dispersion Compensating Fiber (DCF) when used for this purpose. We tried several DCF's and we finally choosed one with a dispersion value of -42.8 ps/nm, which allowed us to achieve an almost perfect compensation, as we obtained at its output pulses only 15.0 ps wide (figure 10b).

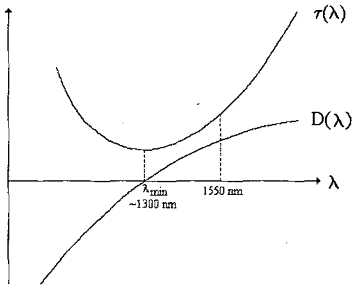

Figure 9. Dispersion and group delay in a SSMF.

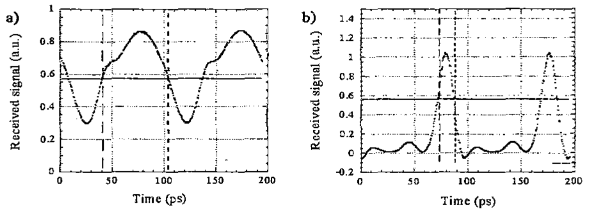

Figure 10. a) Received pulses before compensation (FWHM=64.8 ps). b) Received pulses after compensation (FWHM=15.0 ps).

6. PULSE MULTIPLEXING

In order to obtain an OTDM signal, we first inject a 10 GHz RF signal in a Gain-Switched DFB laser to obtain RZ optical pulses, which we compress to a FWHM of 10 ps. Then, if we want to obtain a 20 Gb/s multiplexed signal, the pulses are split into 2 channels (of 10 Gb/s each) and they are injected into an external modulator (e.g. a Mach-Zehnder electro-optic $LnNbO_3$ modulator), which is modulated with a data signal to transfer the information ('0' and '1') of this signal to the RZ pulses. Each channel is time-delayed half a bit-period and multiplexed, hereby bit-interleaving the channels. This process can be expanded to more channels, and finally the multiplexed signal is injected into the fiber.

In our experiment, we did not have acces to a modulator, so the compressed pulses were just multiplexed in time (bit-interleaved) without modulation. In this case we simply generate two optical pulsed signals, compress the pulses and delay one of the signals half a bit-period before multiplexing and injecting both signals together into the same fiber. In this way we have a pulse of one of the signals between each two pulses of the other one and equidistant to them. Thus, the multiplexed signal has a period half of the original at the expense of reducing the space between pulses. Furthermore, if the pulses are narrow enough, we can iterate the process and mix two of these multiplexed signals (with two channels each) to obtain a four-channel time-multiplexed signal. And we can go on doubling the number of channels until the overlapping of the pulses makes impossible to distinguish them, giving as a result a deteriorated output signal.

For experimental purpose we used the same laser for all channels (passive multiplexing). Then each of the multiplexing stages consisted in a 3-dB coupler (which splits the signal from one fiber into two with half the power in each), a half period delay in one of the two output branches, and another 3-dB coupler to rejoin both signals (figure 11).

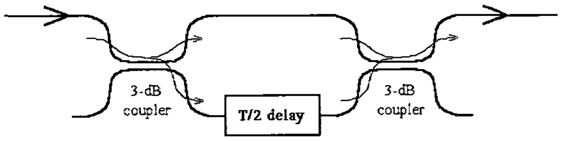

Figure 11. Passive optical multiplexer.

In our first experiment we used only one multiplexing stage, and we obtained pulses at 20GHz, a frequency double of the 10 GHz signal at the input of the multiplexer. As pulses were still clearly separated, we added another stage to get a 40 GHz multiplexed signal (figure 12a). It looked very irregular but it was because of the bandwidth limitation of the oscilloscope, since its appearance substantially improved when we measured it with the streak camera (figure 12b).

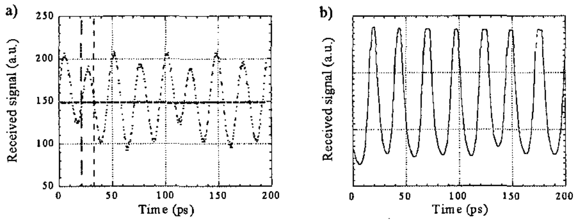

Figure 12. 40 GHz OTDM signal as seen with a) the oscilloscope and b) the streak camera.

So, we added still another multiplexing stage (figure 13) in order to obtain an 80 GHz OTDM signal. Thus, if we had put one bit of information in each pulse (using an OTDM transmitter with an external modulator as explained before) we would have obtained the astonishing transmission rate of 80 Gb/s, divided in 8 channels of 10 Gb/s each. To have an idea of the magnitude of these figures, we could have eight simultaneous users transmitting each all the information contained in the Encyclopaedia Britannica every second!

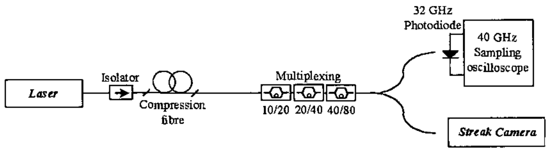

Figure 13. Experimental setup for 80 GHz OTDM signal generation.

The 80 GHz signal (figure 14) was already too irregular to multiplex it again. The problem lay on an imprecise delay in the third multiplexing stage. Furthermore the pulses were too broad, as their FWHM of 10 ps was larger than the 6.25 ps time-slot of a 160 Gb/s transmission. In order to further increase the number of time-multiplexed channels (and so the transmission rate), the multiplexer stages should be very precise, and even more narrow pulses should be obtained.

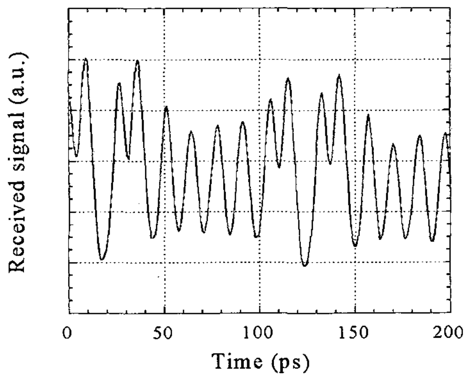

Figure 14. 80 GHz OTDM signal as seen with the streak camera.

7. CONCLUSION

When characterising the laser diode under modulation we have found a certain chirp on it, and we have used it to compress the output pulses from a width of 23.4 ps to only 10 ps.

But we have also seen the pulse broadening caused by this chirp when transmitting over standard fiber. However, we have found a solution for this problem consisting either in using dispersion shifted fiber or in adding a dispersion compensating fiber after the standard fiber.

Finally we have taken advantage of the small width of the output pulses to multiplex as many as 8 channels in an 80 GHz OTDM signal.

Anders Clausen, Henrik Poulsen and Alvaro Buxens are researchers from the COM Center (Center for Communications, Optics and Materials, http://www.com.dtu.dk) at the Technical University of Denmark (http://www.dtu.dk). This university has over many years been doing world-class research in different areas of optical communication techniques for high bandwidth systems, and a large Danish industry has evolved from these research activities. The COM Centre is a new research center that will continue this positive development and take over the research activities of the former Center for Broadband Telecommunications, at the Department of Electromagnetic Systems (http://www.emi.dtu.dk/research/cbt), and the Photonics Group at the Department for Electromagnetic Systems (http://www.mic.dtu.dk/mic/research/photonic.htm). If you are interested in further information on the possibilities of doing projects or studying courses in the field of optical communications please contact via email Alvaro Buxens (aba@emi.dtu.dk) or Henrik Poulsen (hnp@com.dtu.dk).