Wavelength-division multiplexing with femtosecond pulses

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We demonstrate wavelength-division multiplexing with a single broadband femtosecond source by slicing the 3.7-THz spectral bandwidth of 85-fs laser pulses into 16 channels that are modulated individually.

Ultrashort laser pulses have always had a central place in the study of high-speed phenomena as well as in applications that involve very high data rates. With the imminent arrival of practical, compact, and cost-effective femtosecond laser sources,[1] real-world applications of ultrashort laser pulses in communication systems become very likely. In this Letter we present an application of femtosecond laser pulses that is not even directly related to high speed but rather makes use of the large spectral bandwidth offered by short pulses: femtosecond wavelength-division multiplexing (WDM). In this application the data rate is secondary to the spectral bandwidth of the femtosecond source; in fact, our experiment runs at a data rate of only 82 Mbits/s. Such data rates are typical of proposed fiber-in-the-loop systems,[2] which are a practical application for femtosecond sources, because the laser would have to be located at only a central office location and, in this architecture, could be shared among many users.

Conventionally, WDM systems utilize a separate single-frequency laser (usually a distributed-feedback laser) for each WDM channel. The wavelength of each laser needs to be controlled and stabilized individually to ensure that the emission wavelength coincides with the preassigned WDM channels. The use of monolithically integrated multiple-wavelength lasers[3] alleviates some of these problems, although stabilization of the emission wavelength still is required. A novel approach is to use a broadband source that covers all channels simultaneously, such as amplified spontaneous emission from a fiber amplifier[4] or the supercontinuum generated in optical fibers.[5] In this case, the WDM channels are carved out of the broadband spectrum by a passive filter, and wavelength drift of the source does not influence the system.

In this Letter we show that a femtosecond laser is an excellent diffraction-limited broadband source for WDM. A 100-fs laser pulse has an approximately 3-THz spectral bandwidth, enough for 30 channels spaced at 100 GHz, a channel spacing that has been proposed as a standard. There are several advantages in using a femtosecond laser as such a broadband source: First, unlike for incoherent sources, there is no beat noise between different portions of the spectrum within the same channel that limits the total transmission capacity.[4] Second, a femtosecond source is expected to be more stable and more reliable than the supercontinuum generated by nonlinear processes in fibers.[5] Finally, the coherence of the source may be used to aid in channel alignment between transmitter and receiver by setting the WDM channels with spectral pseudorandom codes, similar to the spectral code-division multiple-access (CDMA) technique proposed by Salehi *et al.*[6] We demonstrate the performance of a femtosecond WDM system, using an 850-nm femtosecond source and a 16-channel surface-normal GaAs/AlGaAs multiple-quantum-well (MQW) linear modulator array. Each channel is modulated at the repetition rate of the laser, which is 82 Mbits/s in our demonstration, and error-free performance is reported.

The experimental setup used in our femtosecond WDM experiment is shown in Fig. 1. Femtosecond pulses from a self-focusing mode-locked Ti:sapphire laser with an approximately 9-nm (3.7-THz) spectral bandwidth centered around 850 nm and a roughly 5-mW average power are spectrally and spatially dispersed by a 1200-line/mm diffraction grating and focused onto a reflection-mode linear modulator array by an $f = 50$ mm laser-diode collimating lens (Melles-Griot 06 GLC 006). When the distances between grating and lens and between lens and modulator array are both f, the dispersion of the apparatus is given by $\mathrm{d}x/\mathrm{d}\lambda = f/(d \cos \theta)$, where d and θ are the grating period and the diffraction angle, respectively. For our setup, with $\theta = 60$ deg, $\mathrm{d}x/\mathrm{d}\lambda = 120$ μm/nm, so that the 9-nm FWHM spectrum is spread out to roughly 1 mm on the modulator array. Vertically, the beam is focused to approximately 10 μm, the spot size for each wavelength component. Each channel is then modulated by the modulator array and reflected back

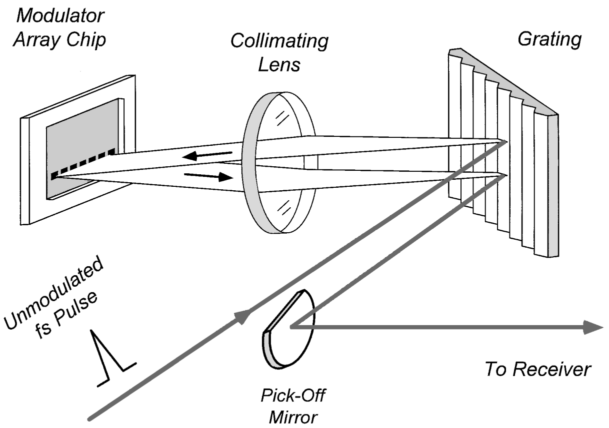

Fig. 1. Experimental setup used to demonstrate femtosecond WDM.

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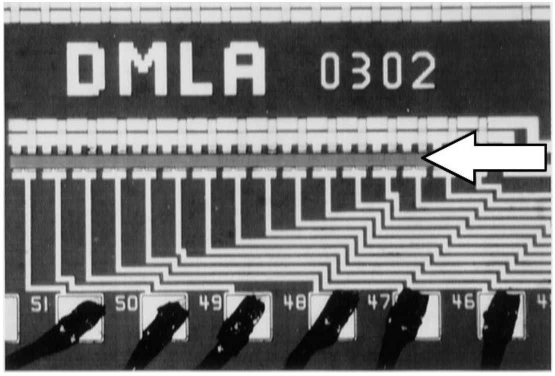

Fig. 2. Photograph of the 16-channel linear MQW modulator array fabricated in GaAs/AlGaAs technology. The arrow indicates the location of the linear array.

along the input path. The modulated signals are recollimated by the lens and grating, picked off by a beam splitter, and transmitted to the receiver setup through a fiber or in free space. The receiver side has a similar configuration, except that the modulators are replaced by detectors.

Figure 2 shows a photograph of the 16-channel reflection-mode modulator array used in the transmitter. It consists of 32 square 20 μm × 20 μm MQW p–i–n diodes spaced by 5 μm. The intrinsic MQW region of the diodes consists of 95 periods of 10-nm GaAs wells and 3.5-nm $Al_{0.3}Ga_{0.7}As$ barriers. This MQW layer is sandwiched between an undoped high-reflectivity dielectric mirror centered at 850 nm and an n^+-doped AlGaAs layer on the bottom, and a p^+-doped AlGaAs layer and an antireflection coating on top. These diodes are electrically defined by only ion implantation, which results in a uniformly reflecting modulator stripe (arrow in Fig. 2) as long as no signals are applied. Each channel consists of two reverse-biased diodes connected in series, and the data signal is applied to the midpoint. The 45-μm width of the diode pair defines the 230-GHz WDM channel bandwidth. Each diode pair is connected to the chip carrier by wire bonds (bottom of Fig. 2). For higher data rates, on-chip drivers may be fabricated on the same wafer by field effect transistor–self-electro-optic effect device (FET-SEED) technology.[7]

To simulate a passive filter that defines the WDM channels, we generate an appropriately delayed pulse pair by passing the femtosecond pulses through a Michelson interferometer. This introduces a sinusoidal modulation to the spectrum, and the modulation frequency can be made to coincide with the channel width by varying the length of one of the interferometer arms. Figure 3(a) shows the portion of the femtosecond spectrum that is reflected from the modulator array measured at the output of the transmitter with a spectral resolution of 0.1 μm. The spectral extent of the channels is indicated by vertical lines in the figure. The 9-nm bandwidth (FWHM) of the spectrum covers all 16 modulators. Both diodes are reverse biased at 9 V, but no data are applied to the midpoint contact, and the output spectrum is simply a replica of the input spectrum. The sinusoidal modulation of the spectrum from the Michelson filter is clearly visible. Figure 3(b) shows the same region with data applied to some of the channels, compared with the unmodulated trace of Fig. 3(a) (dotted curve). The data signals swing between both bias rails of each diode pair, so that the bias for one of the diodes is dropped to zero, while the other diode sees the full voltage drop between the bias rails (2 × 9 V). Because of the quantum-confined Stark effect, the reflectivity of the modulator diode without bias increases, while the reflectivity of the other diode decreases.

We choose differential data encoding because the reflectivity change caused by the quantum-confined Stark effect is a function of the detuning from the exciton peak [see Fig. 3(b)] and also because the Gaussian envelope of the femtosecond spectrum leads to lower intensities toward the extremities of the array. Figure 3(c) illustrates more clearly how logic states 1 and 0 are encoded differentially by means of diode pairs. The reflectivity change for two channels (9 and 10) modulated at logic states 0 (solid curves) and 1 (dashed curves) is shown. For a logic 0, the reflectivity of the left diode (A) is higher than that of the right one (B), while the reflectivity change for a logic 1 is just the opposite. The optical cross talk between adjacent channels is less than −10 dB. The reflectivity change for channels 9 and 10 toward the middle of the array is approximately symmetric. In general, however, the reflectivity change is not symmetric along the entire spectrum, because the reflectivity change is a function of the detuning from the MQW exciton peak. Also, the modulation depth changes along the spectrum.[8] Because of the differential encoding, neither presents a problem for the performance of the system.

We demonstrate the performance of the system by modulating a single channel at the repetition rate of the laser (approximately 82 Mbits/s). In the absence of a differential receiver, we detect the modulated channel with a single-ended avalanche photodiode

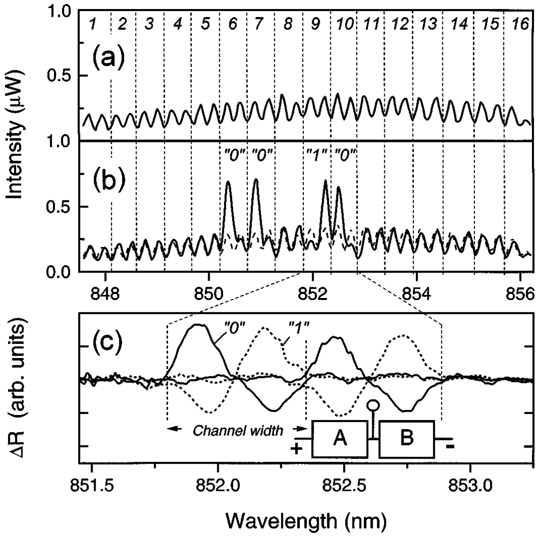

Fig. 3. Differential modulation of the femtosecond pulse spectrum: (a) spectrum reflected from modulator array with no data applied to the array, (b) spectrum after modulation of some of the WDM channels, (c) reflectivity change ΔR for logic 0 (solid curves) and logic 1 (dashed curves) in channels 9 and 10.

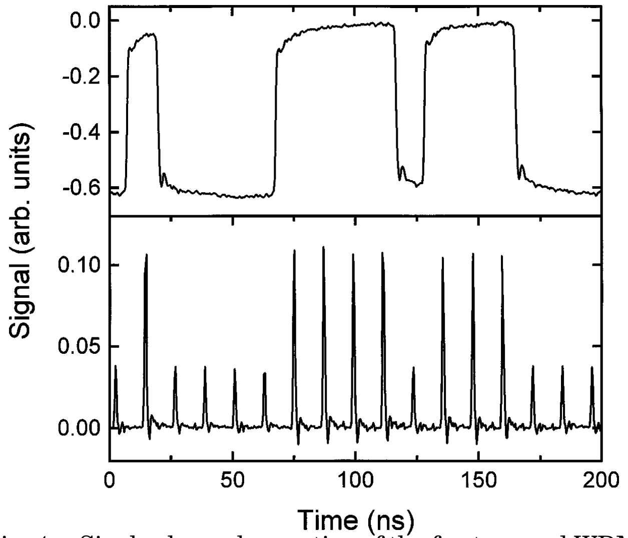

Fig. 4. Single-channel operation of the femtosecond WDM system at 82 Mbits/s. The top waveform is the nonreturn-to-zero data signal applied to the modulator; the bottom trace shows the signal measured at the receiver. The signal consists of a train of pulses with nonreturn-to-zero envelope modulation.

receiver with a 50-nW sensitivity. For this measurement we mount the chip in a high-speed package with high-speed connectors and integrated 50-Ω termination and connect the input to a word generator. The work generator is synchronized to the laser repetition rate. On the receiver side, we use a spatial mask in front of the detector to select only the signal from the single modulator diode (half a channel). The result of the measurement is shown in Fig. 4. The top waveform is the 16-bit word nonreturn-to-zero data signal (5 V peak to peak) applied to the modulator. The bottom trace shows the signal detected at the receiver that consists of a train of pulses with nonreturn-to-zero envelope modulation. Because of the single-ended (not differential) detection and the lower voltage swing compared with that shown in Fig. 3, the modulation contrast ratio is approximately 3:1. Because the modulated data are from a single channel only, pulses displayed in the lower trace no longer are of femtosecond duration but are spread out to a duration of roughly the inverse of the channel bandwidth (≅10 ps). We also modulate a single channel with a pseudorandom bit sequence of length $2^{23} - 1$. The resulting eye pattern measured at the receiver is wide open, indicating error-free operation at 82 Mbits/s for approximately 190 nW of received optical power. In fact, the bit-error rate is entirely limited by the receiver noise in our experiment.

One feature of the femtosecond WDM system is that the information on each channel always is pulsed at the repetition rate of the laser source, as long as there are many longitudinal modes within a channel. Generally, this is considered an advantage because it helps in the recovery of the clock at the receiver. On the other hand, it also is possible to run the source at such a high repetition rate that the comb of longitudinal modes coincides with the WDM channels.[9] Then, each channel contains only a single longitudinal mode. However, the longitudinal modes now have to be carefully aligned with the channel frequencies, not unlike the situation for single-frequency lasers in current WDM systems.

In conclusion, we demonstrate femtosecond WDM that uses a single broadband source to cover all WDM channels simultaneously rather than one that requires a separate laser for each channel. Because compact, diode-pumped femtosecond sources currently are being developed near 850 nm as well as at 1.5 μm, this can be a practical and economical WDM source for short-range WDM systems such as fiber in the loop. This concept also could be used for multichannel interconnects over a single fiber between arrays of transmitters and receivers.

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References

1. D. Kopf, K. J. Weingarten, L. R. Brovelli, M. Kamp, and U. Keller, Opt. Lett. **19,** 2143 (1994); P. J. Delfyett, L. Florez, N. Stoffel, T. Gmitter, N. C. Andreadakis, Y. Silberberg, J. P. Heritage, and G. Alphonse, IEEE J. Quantum Electron. **28,** 2203 (1992); K. Tamura, C. R. Doerr, L. E. Nelson, H. A. Haus, and E. P. Ippen, Opt. Lett. **19,** 46 (1994).
2. N. J. Frigo, P. P. Iannone, P. D. Magill, T. E. Darcie, M. M. Downs, B. N. Desai, U. Koren, T. L. Koch, C. Dragone, H. M. Presby, and G. E. Bodeep, IEEE Photon. Technol. Lett. **6,** 1365 (1994).
3. K. C. Reichmann, P. D. Magill, and U. Koren, IEEE Photon. Technol. Lett. **5,** 9 (1993).
4. J. S. Lee, Y. C. Chung, and D. J. DiGiovanni, IEEE Photon. Technol. Lett. **5,** 1458 (1993).
5. T. Morioka, K. Mori, and M. Saruwatari, Electron. Lett. **29,** 862 (1993).
6. J. A. Salehi, A. M. Weiner, and J. P. Heritage, J. Lightwave Technol. **8,** 478 (1990).
7. T. K. Woodward, A. L. Lentine, and L. M. F. Chirovsky, IEEE J. Quantum Electron. **30,** 2319 (1994).
8. G. D. Boyd, L. M. F. Chirovsky, A. L. Lentine, and G. Livescu, Appl. Opt. **34,** 323 (1995).
9. Y. K. Chen, M. C. Wu, T. Tanbuk-Ek, R. A. Logan, and M. A. Chin, IEEE Photon. Technol. Lett. **3,** 971 (1991).