Demonstration of Optical Orthogonal Frequency Division Multiplexing

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Abstract: This paper demonstrates a new transmitting technique based on a simultaneous multiple channel modulation of ultrafast optical pulse by sending the Fourier Transform (FT) of the time framed signals over a communication channel. This transmission format was designed and found to overcome certain types of channel impairments. The main advantage is that the noise and signal degradation from one particular channel or several channels can be distributed over the entire span of the available frequency resource, so that the particular channels' SNR can be improved regardless of noise source. The trade off is that the other channels' SNR will be affected moderately. This method will be useful for the unknown channel noise pattern, for channel with irregular attenuation mode, and for the channel where the SNR changed dramatically over the entire available span.

Introduction: The successful development of optical communication followed the availability of high quality tunable semiconductor lasers. Such lasers provide a narrow linewidth source with high signal to noise ratio (SNR). The dense wavelength division multiplexed (DWDM) transmission format is a logical solution inherited from FM radio and broadband wireless communication for transmitting more information simultaneously through the communication channel. However, amplitude modulation and detection are still used in the current optical network, which limited the available communication protocols. Commercial network designers have noticed the advantages of frequency or phase modulation scheme to improve the SNR further. However the inherent random noise from different lasers introduces additional noise sources. As an attractive alternative to existing optical communication source components (semiconductor diode lasers), femtosecond pulse shaping provides multi channel outputs from one single mode locked femtosecond laser [1-3] that is coherent and receiving renewing interest in study the information transmission aspect of such source. Further more, the phase of the individual channel can be controlled independently, enabling the applicability of various advanced network architectures.

An application of femtosecond pulse shaping can be frequency division multiplexing (FDM). FDM is a technology that transmits multiple signals simultaneously over a single transmission path, such as a cable or wireless system. Each signal travels within its own unique frequency range (carrier), which is modulated by the data (text, voice, video and etc.). Orthogonal FDM's (OFDM) spread spectrum technique distributes the data over a large number of channels that are created at precise frequencies. OFDM is sometimes called multi-carrier or discrete multi-tone modulation. It is the modulation technique that is used for digital TV in Europe, Japan and Australia. The special arrangement and combination of such frequency spacing provide the orthogonality in this technique that prevents the demodulators from seeing frequencies other than their own. The benefits of OFDM are high spectral efficiency, resiliency to inter symbol interference, and lower multi-path distortion. It is useful in a typical wireless broadcasting scenario where there are multi-path channels (i.e. the transmitted signals arrive at the receiver using various paths of different length due to signal reflection from barrier materials). It becomes very hard to extract the original information because of multiple versions of signal interfere with each other.

Wide applications of OFDM in the European market as the Digital Audio Broadcasting (DAB) standard, in ADSL (asymmetric digital subscriber line) standard and Wireless Local Area Networks and the outlines of using OFDM in the 5.8-GHz band as in IEEE 802.11a, has stimulated the search for the optical realization of such technique. The ISI has become an issue in today's DWDM system. However, the amplitude only modulation provided by existing DWDM system is not enough for this particular application. One femtosecond laser pulse a microwave AOM pulse shaper provides information channels that are equivalent to thousands of slightly frequency tuned semiconductor lasers used in multiple channels optical communication network. At the same time, the coherent communication can be realized by laser phase modulation aspect. The detection of the modulated signal can further be enabled by photon counting devices and quantum communication system. As the need for securing information transmission escalates, this technology will become more and more valuable as the coherent nature of laser allowed flexibility such as channel coding and design. Femtosecond pulse shaping can offer more flexibility than conventional optical communications. The coherent nature of pulse shaping technique allows a more complicated coding scheme. When a non-coherent light source (such as a super luminescent laser diode) is used, spectral efficiency is limited by spontaneous-spontaneous beat noise [4]. However, light sources such as the super continuum generator, the mode-locked laser, and the optical comb generator [5-8] are coherent high-capacity transmitters, and they therefore can provide more efficient transmission. Unlike the time lens method [4] that uses a fiber to chirp the pulse in time, modulated by a fast electro-optic modulator, then compressed by fiber again; Ultrafast pulse shaping permits precise spectrum slicing that will not introduce unbalanced high order chirp, which is useful for OFDM-based architectures. A detail comparison of time domain and spectral domain will help advance both techniques. In essence, AOM pulse shaper method uses microsecond-duration radio frequency pulses to completely control the shape of femtosecond laser pulses, hence achieves dramatic temporal data compression about 10^5.

On the other aspect, when noise source is added to a signal during transmission, such as a strongly distorted waveform in the zero dispersion point of fiber when a high intensity light is propagating in this wavelength simultaneously with the signal source. Such interference is due to fiber nonlinear effect. At the same time, the information can be contaminated in many different ways from the particular channel patterns. The unpredictable nature of such mechanism is that as the signal power changes with the input signal pattern, such change is random by nature, results in a time varying random channel pattern. For example, small nonlinearity of the fiber can result in a channel cross talk when the signal power has value over certain threshold value. The output can change so dramatically that one or a few channels will be totally blocked. As another example, the channel fading and multi-deflection of the wireless signal can distort the signals in both amplitude and phase. Various efforts were made to realize such goal: by using power control (actively) as in the wireless network or dynamical gain equalization filters as in optical communication (passively) [9]. Both techniques can improve data transmission by dynamically adjusted the physical channel to the time varying environment. A technique that utilizes digital data processing results in a reduction of such effect will be valuable. Orthogonal Frequency Division Multiplexing (OFDM) [10] can reduce ISI so that the information transmitted can be as faithful as possible without affected too much by the irregular physical channel or a strong interference.

Proposed femtosecond pulse shaper method in channel equalization: This paper is to establish a new data transmission method by implementing an optical OFDM using femtosecond pulse shaper. The technology we are considering is a relatively new approach to femtosecond laser pulse shaping. It uses microsecond radio frequency pulses driven AOM (which are simple and inexpensive to generate and shape) to control the shape of femtosecond laser pulses. The amplitude and phase of the optical pulses were modulated by the acoustic phonon generated inside the AOM pulse shaper. A typical setup is shown in Fig. 1. The angle (Bragg Angle) between the first order beam (diffracted beam) and the incident laser beam is

$$\theta = \lambda \bullet f_a / V_a \qquad (1)$$

where λ is the optical wavelength in the air, f_a is the acoustic frequency, and V_a is the acoustic velocity. The intensity of light diffracted is proportional to the acoustic power (Pa), and the diffraction efficient (D.E.) is:

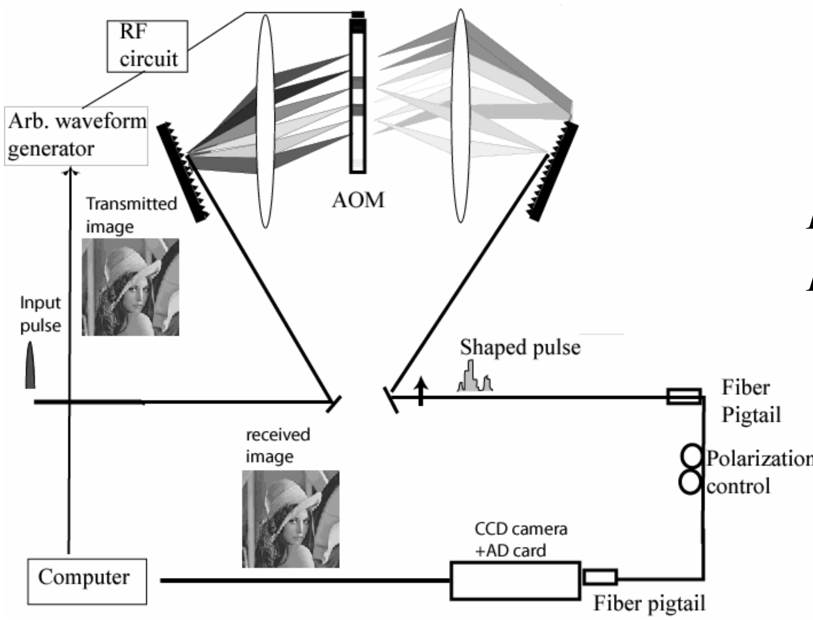
$$\eta = \sin^2[\frac{\pi}{\lambda}(\frac{M_2 P_a}{2}\frac{L}{H})^{1/2}] \approx (\frac{\pi}{\lambda})^2(\frac{M_2 P_a}{2}\frac{L}{H}) \qquad (2)$$

where M_2 is the material figure of merit, L/H is the geometric factor of the AOM. When the acoustic power introduces small D.E., one can approximate a linear relationship between the incident beam and the diffracted beam.

AOM is widely used in creating synchronized radiation as a high-speed modulator and replacing slow mechanical response of tunable delay line. Several distinct programmable spatial pulse-shaping devices have also been suggested: liquid crystal modulators (LCMs), fixed modulation patterns, and spatial actuator arrays. LCM arrays have been widely used and shown to produce shaped ultrafast pulses.[11-16] However, simultaneous phase and amplitude modulation requires two LCM arrays [17], which in itself cast a problem in term of system complexity and cost. The best device used up-to-date has a resolution of up to 512 pixels, but discrete pixellation of the spectrum creates satellite pulses and limits the maximum phase shift to lesser effective pixels. The waveform update rate is limited by reorientation time of the liquid crystal molecules, typically in the order of 50 ms, compared to microsecond update rate provided by an AOM. A single AOM was used to manipulate both spectral phase and amplitude. The laser pulses modulated by AOM can have features as long as 20 ps and as short as 150 fs, including a variety of pulse trains with specified intensity and/or phase profiles.

The AOM pulse shaping enabled DWDM transmission was transparent to both service type and to users. It had the flexibility to assign a set of wavelengths to each end user. The spectrum of the 200 fs Erbium Doped Fiber Laser (EDFL) pulse (Clark ERF laser) was dispersed across the AOM's aperture and was then modulated in a conventional pulse shaper. The past experiment tested 87 channels with channel-spacing of 0.41 nm using a 518-MHz modulator, and 120 channels with channel-spacing of 0.29 nm using an 148-MHz modulator. In both cases, the full width at half maximum (FWHM) of the pulse spectrum was 35 nm, and the updating rate of the AOMs was 3 μs. Starting from the original pulses, this modulation creates time slots of 43 ps and 63.4 ps; thus the equivalent speed of the transmission will be 2.0 Tb/s and 1.9 Tb/s in a highly multiplexed system. Such a system requires a terahertz-multiplexing device, such as the TOAD [18-20]; similar devices can be used as demultiplexers. The idea outlined above has also been proposed [21-22] for a hybrid optical TDM/WDM network, which provides multi-Terabit transmission at reasonable cost. Instead of multiple lasers only one mode-locked laser will be required, which would reduce operating complexity.

To achieve high-quality modulation, the modulation bandwidth should be much lower than the carrier wave frequency. The distortion could be suppressed by using a higher frequency carrier wave, such as the 518-MHz pulse shaper working at 1.55 μm comparing to the traditional 148-MHz pulse shaper. It is interesting to find that higher frequency carrier wave (518 MHz is the UHV working frequency) has produced comparable result with the 148 MHz pulse shaper, despite of different materials, modulation transfer function and polarization of lights. The channel spacing can be as small as 0.04 nm (or 1000 pixels) with a higher power laser and a higher sensitivity receiver, such as a photon counting devices. An optical spectrum analyzer (OSA, HP71451B) collects the intensive spectra of the shaped pulses with a wavelength resolution of 0.1 nm or 12.5 GHz. Such shaped waveform is from a~37 MHz repetition rate. Each channel will have 338 oscillation modes. As the progressing of receiving devices, it is possible to receive and distinguished individual modes inside one channel. The BER of such communication system can be greatly reduced as more modes inside one channel can be detected instead of just the envelope of one channel signal.



$$E_{\text{out}}(\omega) = E_{\text{in}}(\omega) M(\omega)$$
$$E_{\text{out}}(t) = E_{\text{in}}(t) \otimes M(t)$$

Figure 1: The upper optical path is the pulse shaper. It consists of 4f geometry, with the AOM at the center. A computer controls the arbitrary wave generator (AWG), which creates the rf pulses that in turn create the Bragg gratings in the AOM. M(ω) and M(t) is the frequency and time domain modulation function created by the rf. The information encoded in the spectrum is received by the CCD camera. The figure transmitted shows an example of high fidelity image transmission using an AOM pulse shaping -based DWDM protocol.

One of the applications of such technique that we found important in today's complicated communication scheme is the inherent channel equalization capability of the technique. A lost channel can be rescued by using an OFDM format of data transmission. The channel coding can be achieved without any additional hardware requirements. Such idea found its similarity as in the holographic technique, where the optical image is processed by using a holographic instrument for image recording and image retrieval through a media such as a holographic film. One of the advantages of holographic data storage and retrieval is that if there are any damages to the original information, the recovered information is still usable and faithfully represents the original data as long as the damages are within certain conditions. By utilizing such idea in the channel equalization, one can recover the lost data due to the impairment imposed by the certain conditions. The truth is also hold that such technique is not limited to the channel equalization, it is dynamical to some extend, because it is not a time sensitive method. We will show that it can recover the noisiest channel, even under the severe conditions such as a totally lost channel. Simulations of the transmission through various channel patterns with the proposed method and a normal data transmission were compared using computer simulation.

The first channel attenuation pattern we studied is a linearly attenuated WDM connection under an extreme case where one channel was totally blocked. This corresponds to the real situation when the power level of the input light to the EDFA exceeds certain power limit. The output light will have a linear tilting that depends on the power level. In the simulation, in addition to the varied channel attenuation mentioned, there is also a Gaussian noise about 10% of the signal level. This is to simulate random noise and the limited detected signal resolution in real applications. As in Figure 2, comparing the directly detecting method to the proposed method, one can see a BER improvement even with a severe case where the transmitted signal is totally blocked. Notice also that in the proposed method, all channels had same BER. This suggested that the proposed method distributed noise or impairment in one or multiple channels to the other channels, so that it actually effectively improved the overall system performance. In turn, this resulted in eliminating the threshold value variation over the entire receiver.

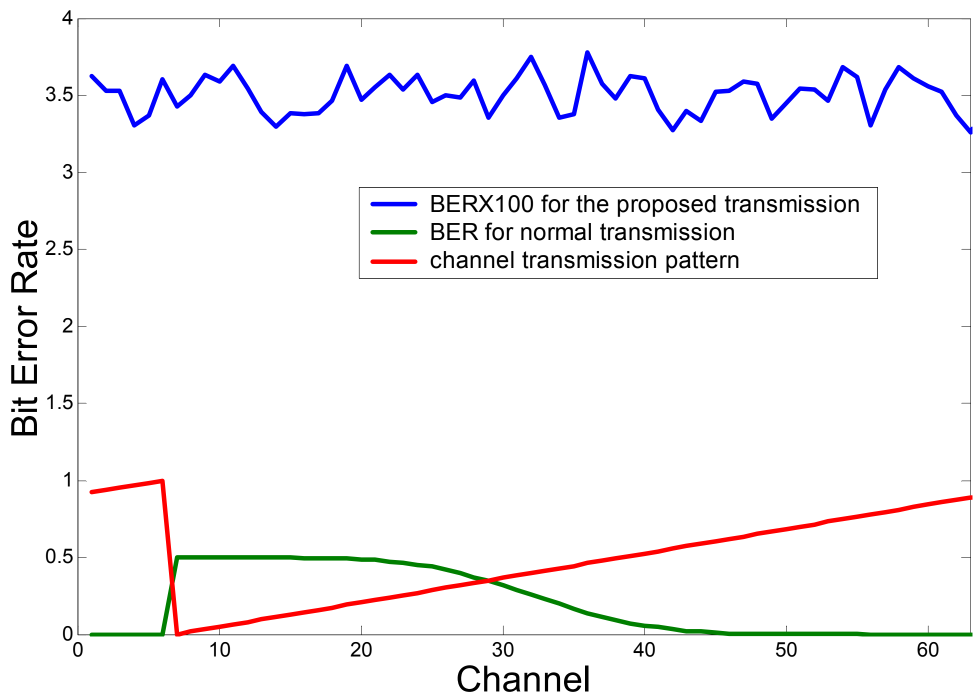


Figure 2. Comparison of the proposed method and the conventional method.

Through simulation, one found that if the noise level was reduced, the transition edge for the directly detection became sharper. At the same time, the overall BER for the signal after FFT reduced as expected. A BER improvement of about 10 times is estimated. Even for a lost channel, the signal will be fully recovered using the FT method. In a realistic situation as an example of losing of one or more channels, the simulation is given in Figure 3. This case is not uncommon in real situation. For example, while the pulse propagated near the zero dispersion wavelength of the fiber, the signal is greatly distorted due to the fiber nonlinearity. It can result in a lost channel.

Within the fiber bandwidth, the variation of transfer function is small. With a combination of optical amplifier and variable arrangement of attenuator, the channel equalization will need to be implemented at fixed distance. Using our method, there is no requirement for the channel equalization (which is generally difficult to implement). This technique can effectively help in the situation where either there is channel fading or the channel characteristic is not known.

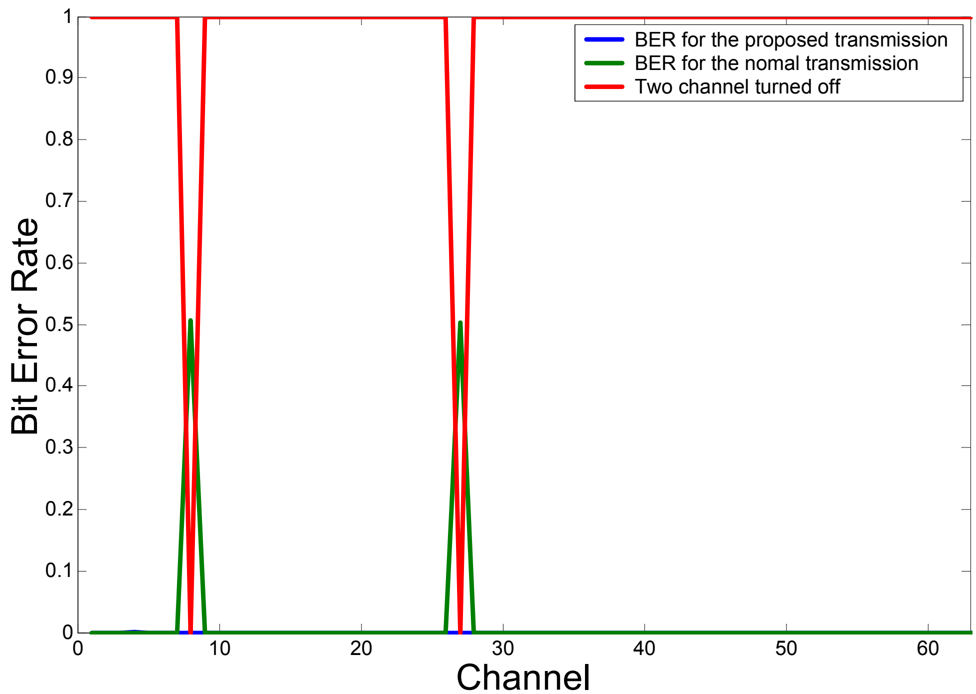


Figure 3. Simulation of situation with two channels turned off. There is only one error during the simulation. A normal transmission will result in a total lost of signal as indicated by a 50% error rate.

Theoretical consideration: It is not necessary to simulate all the available channel models. The problem of exclusive search for the channel model can be replaced by a simpler theorectical study as shown below. This process is straight forward when one compares what happens for the direct sequence mode and the spectral transmitting mode. Suppose that the C(i) is the impulse response of the chanel and the corresponding transfer function is C(ω), where i stands for the label of the channel. The direct sequence signal is S(i). Assuming a OFDM transmision protocol here, signal

$$S(\omega) = \int S(i)e^{-i\omega t}dt \qquad (1)$$

is transmitted over the physical channel. The above is a Fourier transformation of the signal that can be performed in a either software or hardware method. N(ω) is noise of the communication channel, which can be assumed to be additive Gaussian one.

$$N(\omega) = \int N(i)e^{-i\omega t}dt \qquad (2)$$

For the OFDM transmitting mode: the received signal will be

$$C(\omega) \bullet (S(\omega) + N(\omega)) \qquad (3)$$

After an inverse Fourier transformation of the received signal, the coded information can be retrieved as a convolution of C(i) with the sum of S (ω) and the N(i), indicated as:

$$C(i) \otimes (S(\omega) + N(i)) \qquad (4)$$

The resulting signal will be convoluted with the impulse response of the channel under studied.

Compared to the direct sequence, the received signal spectrum will be

$$c(\omega) \otimes (S(\omega) + N(\omega)) \qquad (5)$$

The signal depends directly on the transfer function of the channel. The above explaination actually states that signal distortion dued to the channel irregularity will be replaced by the convolution of the signal with the channel impulse response function, which usually is more regular than the original channel patterns, due to a combination of a linear transformation and a reverse linear transformation.

Depended on the transmitted patterns (eg. RZ or NRZ), the noise level to the signal level can change sigificantly. The convolution of signal with the impulse response function will lead to different result depended on the RZ or the NRZ format. When there is one "0" bit between bits, it is possible that this bit will be mistaken as "1" because the other channel signal will contribute to this bit if the impulse response function has some power in the side channel. From above explanation, one can reach the conclusion that this method depends on and expects a smooth transfer function.

An optical realization: As we mentioned above, sending the optical OFDM signal over the channel will improve the overall signal to noise ratio, by evenly redistributing the noise power. Then, the next question will be how to transimit the signal in a real situation.

For the wireless communication, signals are transmitted with the real and imaginary separately so that the singal can be recovered in the receiver without being affected by the phase distortion. In the optical communicaiton domain, there is simple way to modulate the amplitude of the waveform directly. For the phase modulation, such detected signal relies on an interferometry method, since there is no existing detector that is fast enough for the modulation speed. The transmission of the phase can be done by smart self-detection of the channel phase, then the deducted channel added phase from the sent spectrum. The amplitude is transmitted and detected using the photo diode; the phase profiles are recoverd from the spectral interferometry method. We have tested both amplitude only DWDM transmission, phase only WDM transmission, code devision multiple access (CDMA) and their transmssion over a single mode fiber, a dispersion shifted single mode fiber. We have noticed a great noise immune of such method to the channel distortion.

Comparing to other signal conditioning methods with respect to channel equalization method: for the passive power control, the power equalization is through passive device;

there is no simple way to rescue the lost channel from attenuation. The method proposed provides a cost effective way to reduce the operation complexity, and rescue the lost signal through digital signal processing.

Conclusion: By sending spectrum of the signal over the channel instead of equalizing the signal in the real time, one can mitigate the requirement of the flatness of the EDFA and the channel patterns, the SNR is improved dramatically with this new method. By transmitting the linear combination of the signal instead of signal itself, any local channel impairment will become global. The effect is equivalent to distributing the signal power from the healthy channels to the deteriorated channels. Such advanced technology, although in the lab level, as the advance of the IC circuit, and the speed of current PC, can be easily implemented in a normal education college for the purpose of technology education. The starting cost of such system is on the order of NSF funding level and may enable the college student hands on the advanced current state of art communication.

References:

1. A. M. Weiner, D. E. Leaird, J. S. Patel, and J. R. Wullert, II, “Programmable shaping of femtosecond optical pulses by use of 128-element liquid crystal phase modulator,” *IEEE J. Quantum Electro.*, **28**, pp. 908–920, (1992); A. M. Weiner,"Femtosecond Pulse Processing," Optical and Quantum Electronics, Special Issue on Ultrafast Optoelectronics, **32**, 473-487 (2000).
2. J.X. Tull, M.A. Dugan, and W.S. Warren, “High-resolution, ultrafast laser pulse shaping and its application,” *Adv. Mag. Opt. Reson*., **20**, pp. 1-65 (1996); M.A. Dugan, J.X. Tull, and W.S. Warren, “High-resolution, acousto-optic shaping of unamplified and amplified femtosecond laser pulses,” *J. Opt. Soc. Am., B*, **14**, pp. 1-11, (1997); M. E. Fermann, V. da Silva, D. A. Smith, Y. Silberberg, and A. M. Weiner, "Shaping of Ultrashort Optical Pulses by Using an Integrated Acousto-Optic Tunable Filter," Opt. Lett. **18**, 1505-1507 (1993).
3. Mielke M, Alphonse GA, Delfyett PJ “60 channel WDM transmitter using multiwavelength modelocked semiconductor laser,” ELECTRONICS LETTERS **38**, 368-370 (2002); Shi H, Alphonse GA, Connolly JC, Delfyett PJ, “20x5 Gbit/s optical WDM transmitter using single-stripe multiwavelength modelocked semiconductor laser,” ELECTRONICS LETTERS **34**, 179-181 (1998)
4. J. S. Lee, Y.C. Chung, and D.J.DiGiovanni, “Spectrum-sliced fiber amplifier light source for multichannel WDM applications,” *IEEE Phot. Tech. Lett.,* **5** pp 1458-1456, (1993).
5. L. Boivin, S. Taccheo, C.R. Doeer, P. Schiffer, L.W. Stulz, R. Monnard and W. Lin, “400Gbit/s transmission over 544km from spectrum-sliced supercontinuum source,” *Elec. Lett.*, **36**, pp.335-336 (2000).
6. E. A. De Souza, M. C. Nuss, W. H. Knox, and D. A. B. Miller, “110 channels*2.35 Gb/s from a single femtosecond laser,” *IEEE Photon. Technol. Lett*., **11**, pp.446-468, (1999).
7. S. Bennet, B. Cai, E. Burr, O. Gough, and A.J. Seeds, “1.8-THz bandwidth, zero-frequency error, tunable optical comb generator for DWDM applications,” *IEEE Phot. Tech. Lett*., **11** pp. 551-553 (1999).
8. M. Mielke, G. A. Alphonse, and P. J. Felfyett, “168 Channels X 6 GHz From a Multiwavelength Mode-Locked Semiconductor Laser, ” *IEEE Phot. Tech. Lett.* **15**, pp 501-503, (2003).
9. W. Yang, F. Huang, M. R. Fetterman, J. C. Davis, D. Goswami, and W.S. Warren, “Real time Adaptive Amplitude Feeback in an AOM-Based Ultrafast Optical Pulse Shaping System,” IEEE Phot. Tech. Lett. pp.1665-1667, Vol. 11, No. 12, (1999). C. X. Yu, M. Margalit, E.P. Ippen, and H.A. Haus, “Direct measurement of self-phase shift due to fiber nonlinearity,” *Optics letters*, Vol **23**, 9, pp 679-681 (1998)

10. R. Chang and R. Gibby, “A theoretical study of performance of an orthogonal multiplexing data transmission scheme” *IEEE transactions on communication technology, Vol. Com-16, No. 4,* August 1968.
11. J.X. Tull, M.A. Dugan, and W.S. Warren, “High-resolution, ultrafast laser pulse shaping and its application,” *Adv. Mag. Opt. Reson*., **20**, pp. 1-65 (1996); M.A. Dugan, J.X. Tull, and W.S. Warren, “High-resolution, acousto-optic shaping of unamplified and amplified femtosecond laser pulses,” *J. Opt. Soc. Am., B*, **14**, pp. 1-11, (1997); M. E. Fermann, V. da Silva, D. A. Smith, Y. Silberberg, and A. M. Weiner, "Shaping of Ultrashort Optical Pulses by Using an Integrated Acousto-Optic Tunable Filter," Opt. Lett. **18**, 1505-1507 (1993).
12. A. Efimov and D.H. Reitze, “Programmable dispersion compensation and pulse shaping in a 26-fs chirped-pulse amplifier,” *Opt Lett.* **23**, pp1612-1614, (1998).
13. Marc M. Wefers and keith A. Nelson, "Analysis of programmable ultrashort waveform generation using liquid-crystal spatial light modulators," *J. Opt. Soc. Am. B,* **12**, PP2006-2322 (1995).
14. A.M. Weiner, Y. Silberberg, H. Fouckhardt, D.E. Leaird, M.A. Saifi,M. J. Andrejco, and P.W. Smith, “Use of femtosecond square pulses to avoid pulse break-up in all-optical switching,” *IEEE J. Quant. Electron.*, **25**, PP 2648-2655 (1989); A.M. Weiner, R.N. Thurston, W.J. Tomlinson, J.P. Heritage, D.E. Leaird, E.M. Kirschner, and R.J. Hawkins, “Temporal and Spectral Self-shifts of Dark Optical Solitons” *Opt.Lett.*, **14**, 868-870 (1989)
15. M. Wefers and K.A. Nelson, “Programmable Phase and Amplitute Femtosecond Pulseshaping,” *Opt. Lett.,* **18**, 2032-2034 (1993); M. Wefers and K.A. Nelson, “Analysis of programmable ultrashort waveform generation using liquid-crystal spatial light modulators,” *J. Opt. Soc. Am. B*, **14** 1343-1348 (1995)
16. A. Efimov, C. Schaffer, and D. H. Reitze, “"Programmable Shaping of Ultrabroad Bandwidth Pulses from a Ti:Sapphire Laser,” *J. Opt. Soc. Am. B* **12**, 1968 (1995).
17. D. W. Schumacher, J. H. Hoogenraad, D. Pinkos, and P. H. Bucksbaum, “Programmable cesium Rydberg wavepackets," *Phys. Rev. A* **52**, 4719-4725 (1995).
18. J.P. Sokoloff, I. Glesk, P.R. Prucnal, and R.K. Boncek, “Performance of 250 Gbit/s Optical Time Domain Multiplexed System Using a Terahertz Optical Asymmetric Demultiplexer (TOAD), ” *IEEE Phot. Tech. Lett.,* **5** p98 (1993).
19. J.P. Sokoloff, I. Glesk, P.R. Prucnal, and R.K. Boncek, “Performance of 250 Gbit/s Optical Time Domain Multiplexed System Using a Terahertz Optical Asymmetric Demultiplexer (TOAD), ” *IEEE phot. tech. Lett.*, **6** p98 (1994).
20. J. Glesk, J.P. Sokoloff, and P.R. Prucnal, “Demonstration of All-Optical Demultiplexing TDM Data at 250 Gbit/s” *Elect. Lett.,* **30**, pp339-340 (1994).
21. J. K. Rhee, H. Kobayashi, and W. S. Warren, “Optical frequency domain differential phase shift keying in femtosecond-pulse spectral modulation systems,” *J. Light. Tech.* **15**, pp. 2214, (1997).
22. K. Kobayashi, P.R. Prucnal, and W.S. Warren, “Terabit-per-second Optical network with the Spectral-Domain Modulation,” *Proc. SPIE*, **3231**, pp. 75-86 (1997).

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