Appl. Phys. B 74 [Suppl.], S205–S208 (2002)
DOI: 10.1007/s00340-002-0876-x

Applied Physics B
Lasers and Optics

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Femtosecond all-optical wavelength and time demultiplexer for OTDM/WDM systems

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Received: 14 September 2001/
Revised version: 2 November 2001

ABSTRACT In this contribution we present a proof of concept for a femtosecond all-optical demultiplexer based on the diffraction of a pulsed laser beam by an ultrafast transient refractive index grating formed in barium fluoride. The instantaneous character of the grating is demonstrated by measuring the temporal response of the first diffracted order of an independent laser beam. We achieve an overall switching efficiency of $> 23\%$ ($> 18\%$ for $m = 1$), with an extremely high on-off contrast ratio. Our arrangement provides wavelength-dependent diffraction and shows its potential as a demultiplexer for wavelength division multiplexing.

PACS 42.25.Fx; 42.25.Hz; 42.65.Pc; 42.65.Re; 42.79.Sz

1 Introduction

The insatiable demand for bandwidth in telecommunications these days has its cause in the dramatic growth of multimedia and internet services. Ultrafast all-optical technologies are essential in order to upgrade the present optical time division multiplexed (OTDM), wavelength division multiplexed (WDM) transmission systems and to realize more flexible photonic networks [1]. In the last few years research effort has been made to increase the bit rate beyond 100 Gbit/s per wavelength channel [2–4]. Single-channel 1.28 Tbit/s OTDM transmission has been shown recently [5]. To further increase the bit rate in existing optical fibers, broadband WDM signal generation techniques are necessary. The generation of a wideband supercontinuum (SC) is one of the most useful techniques in this field to create pulsewidth-tunable femtosecond optical pulses over a bandwidth of more than 200 nm [6, 7]. This SC source was successfully used by Kawanishi et al. [8], generating OTDM/WDM signals over 70 nm and demonstrating the transmission at a data rate of 3 Tbit/s (160 Gbit/s at 19 wavelength channels).

To handle future high-speed optical communication and data processing, all-optical switches are key devices, especially in such applications as demultiplexers [9]. Wavelength demultiplexers can be classified by their inherent physical mechanism which uses either diffraction-based or interference-based elements [10].

As an example for the latter, the Symmetric Mach–Zehnder (SMZ) all-optical switch family has attracted considerable attention recently [11, 12], including the original SMZ switch [13] and the Polarization-Discriminating SMZ (PD-SMZ) switch [14]. The SMZ switch is based on optical bandfilling in semiconductors, with an ultrafast rise time enabling switching times down to 200 fs [15]. It requires only rather low control pulse energies in the femtojoule range. As a drawback, however, the repetition rate is limited to about 10 GHz due to the slow relaxation of the bandfilling effect on a nanosecond time scale. Moreover, the extinction ratio between the switched and non-switched signal pulses is only approximately 10 dB [15]. The main limitation for the extinction ratio results from the polarization dependence of the nonlinear phase shift.

The advantage of diffraction-based all-optical switches lies in the simultaneous demultiplexing of all WDM channels. One of the most commonly used techniques relies on transient volume holograms written onto the refractive index of photorefractive crystals by two interfering laser beams [16, 17]. Again, only weak laser intensities are required to control the device. The relatively low charge carrier mobility however limits the switching time to the order of 10^{-8} to 10^{-6}s [16].

Here we demonstrate that the generation of an ultrafast transient grating based on the third-order nonlinear optical Kerr effect [18] allows instantaneous optical switching and simultaneous demultiplexing of WDM and OTDM channels in the femtosecond time regime. The effect offers high-repetition operation combined with an almost unlimited on-off contrast ratio.

2 Experimental principle and set-up

The heart of our device is a transient grating generated in a transparent insulator (in our case barium fluoride) by transferring the interference pattern between two femtosecond pulses into the refractive index of the material via the nonlinear optical Kerr effect [18]. Since our excitation at 1.55 eV is far from any resonances in the 10-eV-bandgap material, the transient grating has an instantaneous response of the order

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of one optical cycle (2.7 fs). It represents a thin slide with the thickness of the spatial pulse extension ($\approx 20\,\mu$m) propagating through the material synchronously with the exciting pulses.

The experimental set-up for our experiments is outlined in Fig. 1: the output from an amplified titanium:sapphire laser (wavelength: 810 nm; pulse duration: < 100 fs; repetition rate: 1 kHz) is split into a pair of pump beams to generate the transient index grating and a third beam which serves as a probe beam after frequency-doubling to 405 nm/10 μJ in an LBO crystal. The intensities of pump 1 and pump 2 are kept fixed at 0.6×10^{12} W/cm^2 each. Both beams are s−polarized and focussed to overlap non-collinearly (angle $\sim 1.8°$) on a 1-mm-thin slide of cleaved barium fluoride with a spot area of 0.2 mm^2 to create the grating. It should be noted here that the absolute angle of incidence, i.e. the angle of the beams to the crystal normal, is not critical in these experiments. The delay between both beams is adjusted to zero such as to provide the most effective grating. In all experiments the total incident intensity is always below the threshold for white light continuum generation.

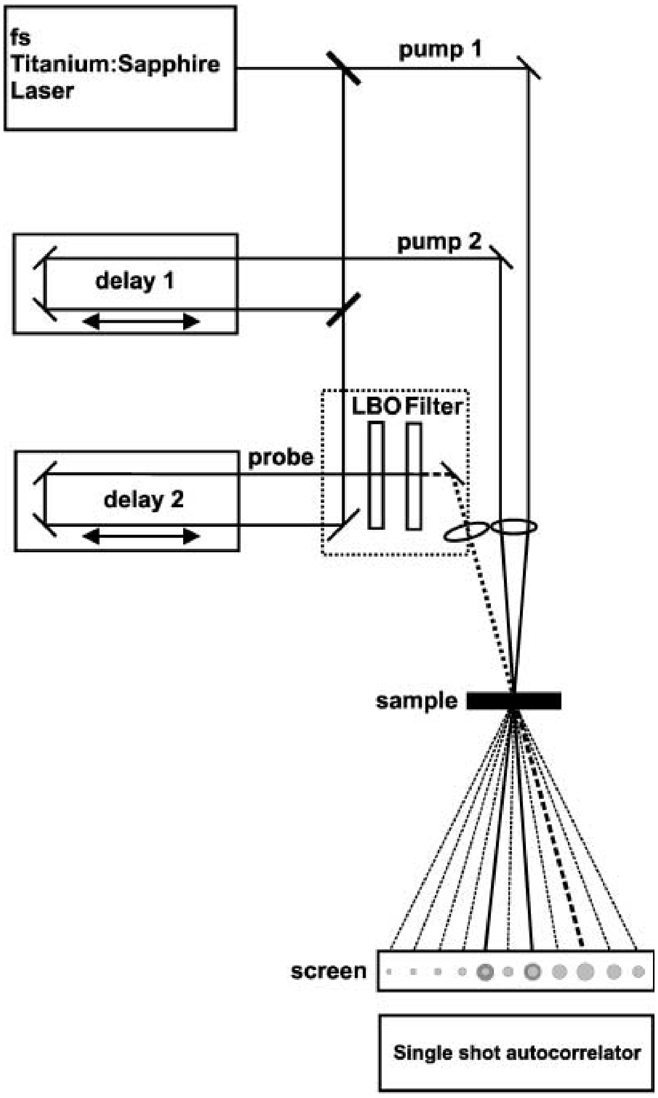

FIGURE 1 Schematic diagram of the experimental setup. The output of an amplified femtosecond Ti:sapphire laser is split into three beams using a conventional pump-probe arrangement. Two delay lines were used to adjust the pulse overlap in time between the channels. For measuring the diffraction efficiency and the lifetime of the index grating the probe beam is frequency-doubled (405 nm) in an LBO crystal

To investigate the grating's potential for possible OTDM/WDM applications, the angular dependence and the efficiency of the diffraction are measured in a first experiment for the blue probe beam, which is separated from the residual fundamental by means of an optical filter (BG 59; Schott) before being focussed onto the sample. The angles between the three non-collinear laser beams are equal and set to 1.8°. The diffraction pattern of the probe beam is monitored on a white paper screen behind the BaF$_2$ crystal and then recorded by a conventional SLR camera.

In a second experiment, the temporal response of the grating is determined. Using the same setup as for the first experiment, the probe pulse (405 nm) delay is scanned across the grating while the intensity variation of the first diffracted order is detected with a photomultiplier. Thus we get a correlation function between grating and probe pulse, from which we obtain an estimate for the lifetime of the grating. Using a single shot autocorrelator (SSA) we characterize the pulsewidth of the pump beams.

3 Results and discussion

3.1 *Probe beam diffraction efficiency*

Figure 2 presents a picture of the diffraction pattern of the frequency-doubled probe beam. It is important to note here that the recording film material is much more sensitive for blue light than for near infrared radiation at 810 nm. As a consequence, the picture shows probe diffraction orders up to $m = 10$, while the pump beams are displayed only faintly. The measurement of the overall diffraction efficiency results in an extremely high value of more than 23% with about 18% being diffracted into first order. The switching contrast appears extremely high, since the experiment delivers background-free diffraction beams.

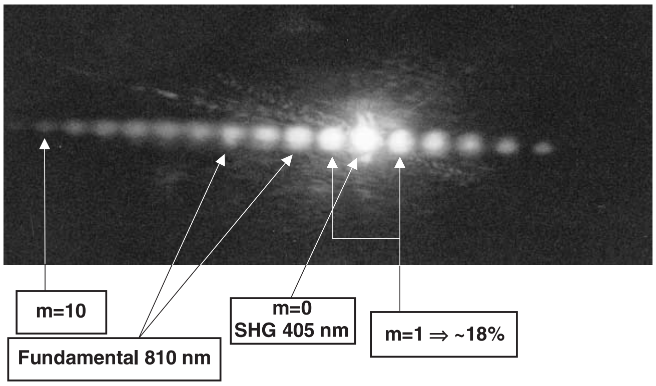

FIGURE 2 Diffraction pattern of the probe beam ($\lambda = 405$ nm, pulse energy $\sim 10\,\mu$J), displayed on a white paper screen. The photo was taken using a conventional SLR camera. Note that the fundamental beams (810 nm) appear very weakly due to the low sensitivity of the recording film material in this wavelength region. On the *left-hand side*, diffracted spots are noticeable up to the order $m = 10$

Analyzing the diffraction, we see that it follows the usual rule for a transmission grating:

$$\sin\theta_m - \sin\theta_\mathrm{i} = m\frac{\lambda}{\boldsymbol{\Lambda}} \quad , \tag{1}$$

where θ_m is the mth-order diffraction angle and θ_i is the angle of the incident probe beam. Both angles are measured relatively to the normal of the grating period vector $\boldsymbol{\Lambda}$. λ is the wavelength of the incident probe beam.

This characteristic feature of the transient grating shows its possible potential for wavelength division multiplexing, since it delivers angular dispersion on a wavelength range limited only by the transmission of the material which, for $\mathrm{BaF_2}$, is ranging from 0.15–12.5 µm. Even demultiplexing of a supercontinuum pulse seems feasible with this ultrafast switching device.

Figure 3 displays a possible switching scheme in a respective node system. The interference of two fs control beams generates a transient index grating in some medium with high nonlinear refractive index n_2, enabling the diffraction of different wavelengths in different directions. Fiber 1 delivers a multitude of different channels ($1\ldots n$) at different wavelengths. Channel 1 of wavelengths λ_1 and λ_2, respectively, will now be switched in the following way: channel 1 of λ_1 into fiber 2 and channel 1 of λ_2 into fiber 3, while all other channels will remain in fiber 1. This demonstrates the possible application of the transient grating as an all-optical demultiplexer for OTDM/WDM systems.

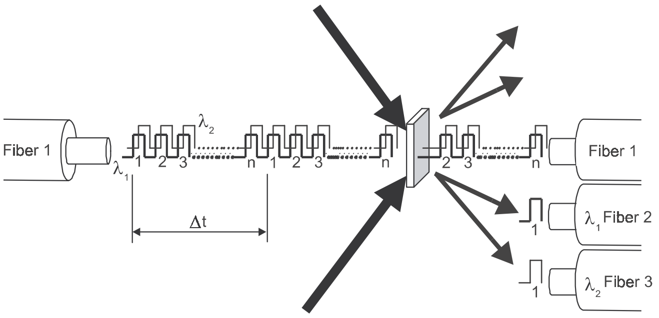

FIGURE 3 A possible switching mechanism in a respective node system. Fiber 1 carries two different pulse trains consisting of ultrashort pulses at two different wavelengths. One pulse train consists of n different signals with a period of Δt. A nonlinear medium is introduced at the crossover point of the two pump laser beams. Signal 1 of pulse train λ_1 is switched to fiber 2, while signal 1 of pulse train λ_2 is switched to fiber 3. All other signals $(2-n)$ remain in fiber 1

3.2 *Diffraction dynamics*

To check the instantaneous character of the index grating, we measure its temporal response via the grating-probe correlation function, monitoring the first diffracted order of the blue probe beam. From our single-shot autocorrelation, we determine the fundamental pulse duration during these experiments to be 120 ± 3 fs at the sample. A Gaussian fit of the measured grating–probe correlation function (Fig. 4) yields a FWHM (full width at half maximum) of 152 ± 7 fs. Assuming that the duration of the blue pulse is about 20% shorter than its fundamental (due to gain narrowing), we can deconvolute the correlation function according to [19]:

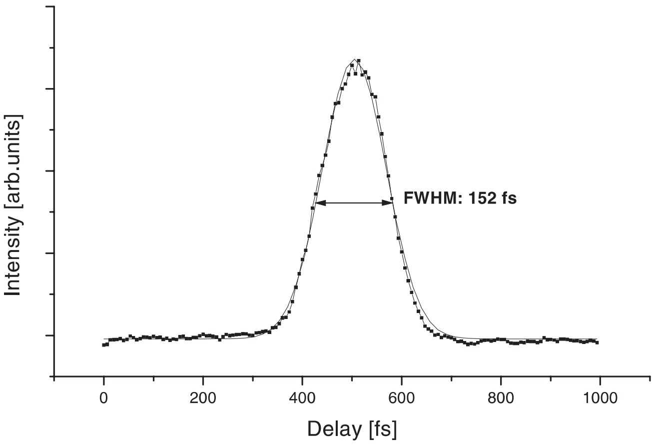

FIGURE 4 Correlation function of the first diffracted order ($m = 1$) of the SHG probe beam. The experimental data is fitted assuming a Gaussian pulse shape

$$\tau_\mathrm{grating} = \sqrt{2} \times \tau_\mathrm{corr} - \tau_\mathrm{probe} \quad . \tag{2}$$

This yields a duration of the grating of

$$\tau_\mathrm{grating} = \sqrt{2} \times 152\,\mathrm{fs} - 0.8 \times 120\,\mathrm{fs} = 119\,\mathrm{fs} \quad . \tag{3}$$

We can thus state that within the precision of our experiment, the grating duration is indeed limited by the duration of the generated pulse. Consequently, the response is limited only by the transversal dephasing time T_2, which is of the order of fs [20].

3.3 *Practical aspects*

We investigated the diffraction of a probe beam by means of an ultrafast transient index grating. For practical applications such as, for instance, a demultiplexer in an OTDM/WDM system, some difficulties have to be overcome. In the field of telecommunications, high repetition rate sources with comparable low output power are widely used. On the other side, femtosecond laser systems with GHz repetition rates are not commercially available yet, but first approaches were shown recently [21]. Moreover, the nonlinear refractive index in barium fluoride is relatively low. This therefore requires high intensities of the overlapping pulses in order to get sufficient grating contrast. A reduction of the required intensities may be achieved using materials with a higher Kerr-nonlinearity, e.g. lead doped glasses, or specifically designed polymers (e.g. polydiacetylene, like PTS), provided they are still sufficiently non-resonant to keep the ultrafast response. Then, the effect may be used with available high repetition rate diode-based systems. Additional problems that must be overcome prior to an application in telecommunication are, for example, the synchronization between the grating and the data stream, or difficulties connected with a possible chirp of the data pulses.

In conclusion, we have presented new results of an ultrafast optical switching device based on an instantaneous index grating due to the nonlinear optical Kerr effect. We measured the lifetime of the grating and gave a strong indication that it is only limited by the pulsewidth of the laser. The reaction time is of the order of one optical cycle. Additionally, we showed that the device is able to diffract additional independent beams with a high efficiency and an extremely large on-off contrast ratio. The diffraction of further beams is identical to that of a conventional transmission grating, and the results demonstrate the possibility of multiple-wavelength switching on a femtosecond time scale.

REFERENCES

1 T. Morioka: ‘Ultrafast optical technologies for large-capacity OTDM/WDM transmission’. In: Ultrafast Electronics and Optoelectronics (UEO) 2001 26/UWB3-1, Lake Tahoe, Nevada, USA (2001)
2 S. Kawanishi: IEEE J. Quantum. Electron. **QE-34**, 2064 (1998)
3 V.W.S. Chan, K.L. Hall, E. Modiano, K.A. Rauschenbach: IEEE J. Lightwave Technol. **16**, 2146 (1998)
4 M. Nakazawa: ‘Toward terabit/s single-channel transmission’. In: OFC’99 (Optical Fiber Communication), FI1, 132 (1999)
5 M. Nakazawa, T. Yamamoto, K.R. Tamura: Electron Lett. **36**, 2027 (2000)
6 T. Morioka, K. Uchiyama, S. Kawanishi, S. Suzuki, M. Saruwatari: Electron. Lett. **31**, 1064 (1995)
7 T. Morioka: Electron. Lett. **32**, 836 (1996)
8 S. Kawanishi, H. Takara, K. Uchiyama, I. Shake, K. Mori: Electron Lett. **35**, 826 (1999)
9 S. Nakamura, K. Tajima, Y. Sugimoto: Appl. Phys. Lett. **66**, 2457 (1995)
10 G.P. Agrawal: *Fiber-Optic Communication Systems* (Wiley-Interscience, New York 1997)
11 R. Hess, M. Caraccia-Gross, W. Vogt, E. Gamper, P.A. Besse, M. Duelk, E. Gini, H. Melchior, B. Mikkelsen, M. Vaa, K.S. Jepsen, K.E. Stubkjaer, S. Bouchoule: IEEE Photonics Technol. Lett. **10**, 165 (1998)
12 S. Diez, C. Schubert, R. Ludwig, H.-J. Ehrke, U. Feiste, C. Schmidt, H.G. Weber: Electron. Lett. **36**, 1484 (2000)
13 K. Tajima: Jpn. J. Appl. Phys. **32**, L1746 (1993)
14 K. Tajima, S. Nakamura, Y. Sugimoto: Appl. Phys. Lett. **67**, 3709 (1995)
15 S. Nakamura, Y. Ueno, K. Tajima: IEEE Photonics Technol. Lett. **11**, 1575 (1998)
16 K. Kuroda, M. Saffman, A. Zozulya (Eds.): *Photorefractive Materials, Effects, and Devices*, Special Feature: J. Opt. Soc. Am. B **15**, 1967 (1998)
17 H.J. Eichler, P. Günter, D.W. Pohl: *Laser-Induced Dynamic Gratings* (Springer, New York, Berlin 1986)
18 T. Schneider, D. Wolfframm, R. Mitzner, J. Reif: Appl. Phys. B **68**, 749 (1999)
19 R. Guenther: *Modern Optics* (Wiley, New York 1990)
20 J.C. Diels, W. Rudolph: *Ultrashort Laser Pulse Phenomena* (Academic Press, San Diego 1996)
21 M.D. Pelusi, Y. Matsui, A. Suzuki: Electron. Lett. **35**, 734 (1999)