

clipping carrier was absent [1]. Consequently, the power control requirement on S-CDMA technique can be relaxed significantly.

Although the added coherent clipping carrier provides an excellent OBI suppression capability and a large system DR, it consumes a significant amount of RF driving power to laser A. Conversely, it is conjectured that the clipping carrier can suppress OBI more effectively than the S-CDMA signal. It is therefore important to find a balance between the driving power levels of the clipping carrier and the S-CDMA signal. Fig. 5 shows the results of P_A against different values of MI_S and MI_C when the total driving power was fixed. We can see that there indeed exists an optimum (coherent) combination of the clipping carrier and the S-CDMA signal power, i.e. a minimum P_A of -30.5 dBm was obtained when $MI_S = 150\%$ and $MI_C = 130\%$. Also, when most of the driving power is allocated to either the clipping carrier or the S-CDMA signal, the resultant power levels of P_A were increased by 3 dB compared to the optimum case.

Conclusion: In this Letter, we have experimentally demonstrated that an in-band clipping carrier, when coherently combined with a Walsh-code-based S-CDMA signal, can effectively suppress OBI in a PON or WDMA network. When the total driving power was fixed, we found that an optimum combination ratio of the two signals exists to achieve a maximum system power budget. Our experimental results showed that, under the condition of no bandwidth wasted on the in-band clipping carrier, a negligible system power penalty can be achieved even when the OBI-induced intensity noise was as high as -90.9 dB/Hz. In addition, a large system dynamic range of 10 dB can be obtained to relax the tight power control requirement on S-CDMA signals.

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References

- HSIAO, C.C., WANG, B.H., and WAY, W.I.: 'Multiple access in the presence of optical-beat and co-channel interference using Walsh-code-based synchronised CDMA technique', *IEEE Photonics Technol. Lett.*, 1997, **8**, pp. 1173–1175
- WOODWARD, S.L., LU, X., DARCIÉ, T.E., and BODEEP, G.E.: 'Reduction of optical-beat interference in subcarrier networks', *IEEE Photonics Technol. Lett.*, 1996, **8**, pp. 694–696
- SASAI, H., YAMAMOTO, H., UTSUMI, K., and FUJITO, K.: 'Optical access links suppressing optical beat interference with FP-LDs for microwave transmission'. Int. Topical Meeting on Microwave Photonics, Tech. Dig., 1996, pp. 237–240
- FELDMAN, R.D., WOOD, T.H., RAYBON, G., and AUSTIN, R.F.: 'Effect of optical beat interference on the dynamic range of a subcarrier multiple access passive optical network using Fabry-Perot laser', *J. Lightwave Technol.*, 1996, **5**, pp. 711–715
- WOOD, T.H., and SHANKARANARAYANAN, N.K.: 'Operation of a passive optical network with subcarrier multiplexing in the presence of optical beat interference', *J. Lightwave Technol.*, 1993, **10**, pp. 1632–1640

Time-space-conversion optical signal processing using arrayed-waveguide grating

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Indexing terms: Optical communication equipment, Gratings in fibres

The authors propose time-space-conversion optical signal processing using an arrayed-waveguide grating. It provides a wide time window, compatibility with fibre optics, compactness, and integration capabilities. Pulse train generation is demonstrated to confirm its performance at the wavelength of $1.55\mu\text{m}$.

Optical signal processing based on time-space-conversion is highly attractive, especially for ultrafast signal processing applications in high-speed optical communication systems with a data rate of more than 100 Gbit/s. Such processing enables many operations such as the formation, reshaping, pattern recognition and even routing of an ultrafast bit stream, which are difficult to do by traditional electronic means. This technology has been widely demonstrated in the wavelength range of $0.4\text{--}0.85\mu\text{m}$ by using free-space optics with diffraction grating pairs and lenses [1–4]. In such a grating system, however, the time window is determined by the size of the diffraction grating and spatial filter, and it is difficult to make it compact.

In this Letter, we propose time-space-conversion optical signal processing using an arrayed-waveguide grating (AWG) and demonstrate pulse train generation at the communication wavelength of $1.55\mu\text{m}$.

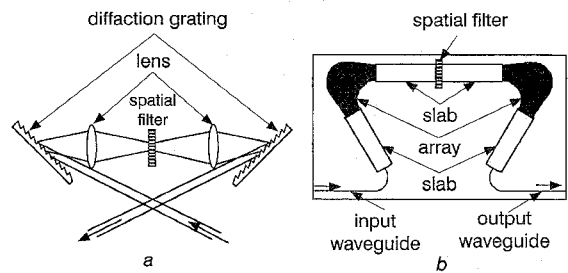


Fig. 1 Schematic diagram of time-space-conversion processing system using diffraction gratings (DGs), and arrayed-waveguide gratings (AWGs)

a DGs
b AWGs

Fig. 1 shows a schematic diagram of time-space-conversion processing systems using *a* diffraction gratings (DGs) and *b* arrayed-waveguide gratings (AWGs). In both systems, a temporal waveform carries spatial information on the dispersive element and is converted to a temporal frequency spectrum in the focal plane. The frequency spectrum is then modulated in parallel by a spatial filter and reconverted to a reshaped temporal waveform. When the waveform $u(t)$ is incident on the dispersive elements, such as a DG and an AWG, with the incident angle so as to produce the surface normal diffracted beam with the carrier lightwave frequency ν_0 , it is transformed into $u(t - n\beta x/c)$ on the x axis lying along the exit surface of the dispersive element, where β is a dispersion parameter, c is the speed of light, and n is the refractive index of the media through which the light propagates. The dispersion parameter is given as

$$\beta = \nu_0 \frac{d\theta}{d\nu} = \frac{m c \nu_0}{n d \nu^2} \quad (1)$$

where m is the diffraction order and d is the periodical pitch of the dispersive elements. The maximum time window T_0 is determined by $n\beta x/c$, hence:

$$T_0 = \frac{n\beta}{c} N d = \frac{mN}{\nu_0} \quad (2)$$

where N is the number of illuminated lines of the DG or waveguides of the AWG. The diffraction order of the DG is limited to a small value, typically $m = 1$, as it is proportional to the grating pitch, whereas AWGs usually have a large diffraction order (30–200) as it is proportional to the path length difference between neighbouring waveguides [5]. This means we have some design flexibility in that the dispersion parameter value can be made quite large for an arbitrary diffraction order in the AWG system, and this results in a long total time window even if N is limited to a smaller value than that in the DG system.

Conversely, in the DG system pulsewidth τ in the pulse trains is usually limited by the spatial filter size, H , as follows:

$$\tau \geq \frac{c f}{n d \nu_0^2 H} \quad (3)$$

where f is a focal length of a lens. The pulsewidth in the AWG system, however, is determined only by the diffraction order such that

$$\tau \geq \frac{m}{\nu_0} \quad (4)$$

Finally, we obtain the maximum bit number K_{max} in the bit stream as $T_c/2\tau$;

$$K_{max} = \frac{\nu_0 n H N d}{2c f} \quad \text{for the DG system} \quad (5)$$

$$K_{max} = \frac{N}{2} \quad \text{for the AWG system} \quad (6)$$

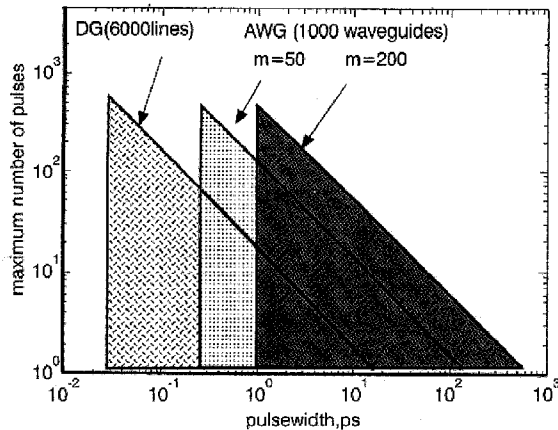


Fig. 2 Pulse processing performance comparison between AWG and DG at wavelength of 1.55 μm

Assume incident angle of light beam to DG is 60°, and size of spatial filter is one-tenth of lens focal length

Fig. 2 compares the pulse processing performance of an AWG and a DG at a wavelength of 1.55 μm . Conventional grating systems are suitable for the synthesis of pulses with a width of around 100fs within a time window of < 30ps. AWG systems, however, are suitable for handling subpico- to several picosecond pulses with long time windows up to one nanosecond. Moreover, they are compact, compatible with fibre optics, and can be integrated with other planar lightwave circuits (PLCs).

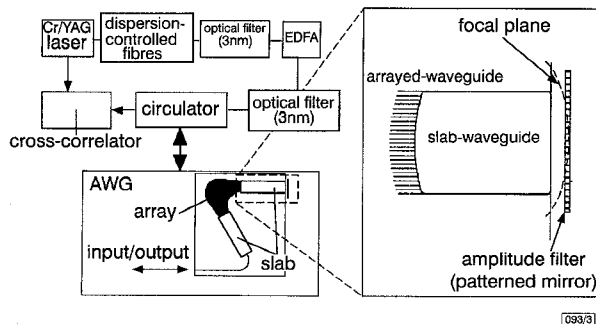


Fig. 3 Experimental setup for pulse train generation with AWG

To confirm the feasibility of time-space conversion processing in an AWG system, we fabricated reflection-type AWG optical circuits and demonstrated pulse train generation. The experimental setup and a schematic diagram of the AWG are shown in Fig. 3. The AWG consists of an I/O waveguide with a singlemode fibre pigtail, slab waveguides with a focal length of 22.6mm, and an array of 340 waveguides. The diffraction order is 59 at the central frequency of 193.2THz (1552nm), so the minimum pulsewidth is ~0.2ps. The resolving power is ~10GHz, which means that the time window is ~100ps. The light source was a Cr:YAG mode-locked laser that generates transform limited pulses (pulsewidth: < 0.1ps; repetition rate: 200MHz). Dispersion control fibres were used to compensate the dispersion of the experimental setup. Femtosecond pulses were spectrally sliced and amplified by an EDFA. After the second optical filter, the pulsewidth was 1.1ps when dispersion was compensated; the centre wavelength was 1549nm and the spectral width was 2.3nm.

The pulses were input into and output from the AWG through an optical circulator. An amplitude spatial filter (patterned mirror) was placed on the focal plane, close to the facet of the AWG. The focal plane should have a slight curvature, although the spatial filter has a flat surface. The maximum phase mismatch due to the

geometrical difference is calculated to be < $\pi/4$, which is negligible. Synthesised pulse waveforms were measured by a cross correlator [6]. Fig. 4a and b show the observed waveforms of 120 and 240GHz repetition rate for the amplitude filters with a mirror spacing of 60 and 120 μm , respectively. The pulsewidth within the pulse train was ~1.2ps, almost the same as the input pulsewidth. The non-uniform envelope of the pulse train limited the time window (50ps), which is due to the binary amplitude pattern of the spatial filter we used.

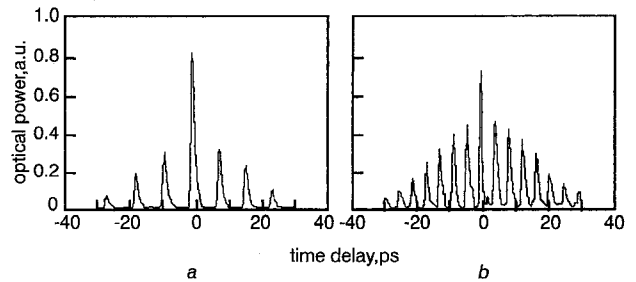


Fig. 4 Examples of pulse train generation measured by cross-correlator

a 120GHz pulse train
b 240GHz pulse train

In summary, we have proposed time-space-conversion optical signal processing using an AWG and demonstrated pulse train generation to confirm its performance at a wavelength of 1.55 μm . This will be a key technology for signal processing in future high-speed optical communication systems.

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References

- WEINER, A.M.: 'Femtosecond optical pulse shaping and processing', *Prog. Quant. Electron.*, 1995, **19**, pp. 161-237
- SUN, P.C., MAZURENKO, Y.T., C. CHANG, W.S., YU, P.K.L., and FAINMAN, Y.: 'All-optical parallel-to-serial conversion by holographic spatial-to-temporal frequency encoding', *Opt. Lett.*, 1995, **20**, pp. 1728-1730
- NUSS, M.C., LI, M., CHIU, T.H., WEINER, A.M., and PARTOVI, A.: 'Time-to-space mapping of femtosecond pulses', *Opt. Lett.*, 1994, **19**, pp. 664-666
- EMA, K., KUWATA-GONOKAMI, M., and SHIMIZU, F.: 'All-optical sub-Tbit/s serial-to-parallel conversion using excitonic giant nonlinearity', *Appl. Phys. Lett.*, 1991, **59**, pp. 2799-2801
- TAKAHASHI, H., SUZUKI, S., and NISHI, L.: 'Wavelength multiplexer based on SiO₂Ta₂O₅ arrayed-waveguide grating', *J. Lightwave Technol.*, 1994, **12**, pp. 989-995
- ISHIDA, Y., and NAGANUMA, K.: 'Characteristics of femtosecond pulses near 1.5 μm in a self-mode-locked Cr³⁺:YAG laser', *Opt. Lett.*, 1994, **19**, pp. 2003-2005

1 m long continuously-written fibre Bragg gratings for combined second- and third-order dispersion compensation

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Indexing terms: Gratings in fibres, Optical dispersion, Optical communications

The authors present the realisation of high-quality 1m long continuously-written fibre Bragg gratings designed to compensate both second- and third-order fibre dispersion. These compact devices are ideal for counteracting the effects of fibre dispersion in high bit rate transmission systems.