As a next step the PMD compensator was inserted. The controller maximised the 25 and 40GHz power levels. The autocorrelation trace reveals a slightly narrower pulse with a deconvolved 5.2ps width (Fig. 2b). Similar pulse peaking has already been found in NRZ experiments [3, 6, 8]. Then the emulator was inserted with 10 + 6ps of DGD in the PMF pieces. The deconvolved pulsewidth was now 5.4ps but the autocorrelation pedestal (3% back-to-back) increased to 7.5% (Fig. 2c). With 10 + 10ps of DGD in the emulator the deconvolved pulsewidth was 5.8ps and the pedestal 12% (Fig. 2d). However, the autocorrelation function exaggerates the true pedestal, as may be seen from a fitted calculation result assuming the superposition of two Gaussian pulses (Fig. 2e). There is very little intersymbol interference. For comparison we give also an autocorrelation trace for the emulator plus compensator with the control signals minimised rather than maximised. In this case the original pulses essentially disappear due to PMD (Fig. 2f).

A dynamic measurement was made with the 10 + 6ps emulator and the compensator. Starting from an initial standsill the motorised fibre polarisation transformers were made to turn successively faster.

![Fig. 3 Recorded spectral power](image)

Top trace: control on
Bottom trace: control off
(i) eight fibre coils in emulator start turning

Fig. 3 (upper trace) shows an aggregate control signal obtained by linearly combining the 40 and 25GHz power level signals. Part of the signal variations can be attributed to polarisation dependence (~1dB) of the components following the compensator. For a comparison the measurement was repeated when the control was off. Large signal fluctuations occurred as expected when the fibre coils started to turn (Fig. 3, lower trace). The experiment shows that optical PMD compensation with a simple, purely electrical PMD detection scheme is also possible for RZ signals.

Conclusions: For the first time to our knowledge, the PMD of RZ signals has been compensated. A distributed LiNbO,

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References

Spectral encoding and decoding of 10Gbit/s femtosecond pulses using high resolution arrayed-waveguide grating


A 10Gbit/s, 810fs, return-to-zero signal is spectrally encoded, transmitted over a 40km dispersion shifted fibre, and decoded using a photonic spectral encoder and decoder pair that uses high resolution arrayed-waveguide gratings and phase filters. A 255 bit binary phase code with the maximum length sequence is used for spectral coding.

Introduction: A combination of optical code division multiplexing (OCDM) with time division multiplexing (TDM) and wavelength division multiplexing (WDM) improves the signal spectrum efficiency and flexibility of fibre optic communication systems. A photonic encoder/decoder pair is one of the key components of such an optical CDM system. Studies have been made on encoding and decoding optical pulses through the use of diffraction grating pairs [1, 2] and optical transversal filters [3]. These diffraction grating systems, however, do not have sufficient spectral resolution for high signal spectrum efficiency, while optical transversal filters are not easy to use with WDM systems. In this Letter we describe a photonic spectral encoder and decoder pair [4] that uses high-resolution arrayed-waveguide gratings (AWGs).

Configuration and operating principle of spectral encoder/decoder: We used a reflection-type AWG, which is polarisation insensitive, and a spatial phase filter on the spectral plane, as shown in Fig. 1. This configuration can also be used for other photonic signal processing operations, including dispersion compensation and
phase-shift keying direct detection [5-7]. The AWG encoder spectrally decomposes the input pulses into their frequency components, modulates each phase with the encoding filter, and reforms the waveform. Binary phase encoding with the maximum length sequence (M-sequence) is used. The spectral bit width was set at 1/(TwD, timeslot). The phase function of the filter, \( H_m(\omega) \), is written as

\[
H_m(\omega) = \exp[i\pi M_k(\Omega(\omega))] \tag{1}
\]

where \( M_k(x) \) is the \( x \)th element of the \( k \) stage M-sequence, \( \omega \) is the angular frequency, \( \omega_0 \) is the centre frequency of the AWG and \( \delta \omega \), which is \( 1/(TwD, \text{timeslot}) \), is the bit width of the filter. The output waveform from the AWG encoder is described approximately as

\[
\{f(r)e^{i\omega_0 r}\} \ast h_m(r) \tag{3}
\]

where \( f(t) \) is the input pulse waveform and \( h_m(t) \) is the Fourier transform of \( H_m(\omega) \). The M-sequence is a pseudorandom sequence, so the output waveform is spread out within the timeslot without a clear peak. After transmission with dispersion compensation, the signal is again spectrally modulated by the AWG decoder, which has the same filter. The waveform output from the AWG decoder is given by

\[
\{f(r)e^{i\omega_0 r}\} \ast F[H_m(\omega)H_m(\omega')] \quad (F: \text{Fourier transform}) \tag{4}
\]

Fig. 1 Configuration of photonic spectral encoder/decoder

Fig. 2 Experimental setup for spectral encoding and decoding

Results and discussion: Waveforms at points A, B, and C in Fig. 2 were measured by a cross-correlator after dispersion compensation, as shown in Fig. 3A. B, C1 and C2. The decoded waveform in the back-to-back configuration C1 had a clear peak with a width of 1.88 ps when the decoding filter was in the correct position. In contrast, the decoded waveform C2 had no clear peak when the position of the decoding filter was shifted by an amount over 2 bits. These results indicate that the proposed spectral encoder and decoder basically work well. To confirm the feasibility of the AWG spectral encoder and decoder, bit error rates (BERs) were measured.

The decoded signal was received by a conventional 10 Gbit/s optical receiver. The BERs were measured against the averaged optical power to EDFA3, as shown in Fig. 4. The open circles, closed circles, and closed squares, respectively, show BERs for a back-to-back configuration, after transmission with launching powers \( P_L \) of 5 and 10 dBm. There was no significant sensitivity...
penalty up to a $P_\text{p}$ of 5dBm. Error-free (BER < $10^{-9}$) transmission was successfully achieved when $P_\text{p} < 10$dBm. A high launching power to the DSF with very low dispersion was acceptable because the encoded pulse energy was spread over the time slot. Inset A shows the autocorrelation of the decoded pulse after 40km transmission with an autocorrelation width of ~3ps. A clear eye opening was observed, as shown in Inset B.

**Conclusion:** Error-free encoding and decoding of a 10Gbit/s RZ, 20-1 PRBS signal through a 40km transmission fibre was successfully demonstrated using the AWG spectral encoder and decoder pair. The encoder and decoder pair can be used in optical CDM systems with ultra-high-speed optical thresholders.

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-H. Tsuda, H. Takenouchi, T. Ishii and C. Amano (NTT Photonics Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa, 243-0188 Japan)

-E-mail: tsuda@aecl.ntt.co.jp

K. Okamoto and T. Goh (NTT Photonics Laboratories, 162 Shirakata-Shiinane, Tokai, Ibaragi, 310-1196 Japan)

K. Sato and A. Hirano (NTT Network Innovation Laboratories, 1-1 Mikari-no-oka, Yokosuka, Kanagawa, 239-0847 Japan)

T. Kurokawa (Tokyo University of Agriculture & Technology, 2-24-16 Nakamachi, Koganei, Tokyo, 184-8588 Japan)

**References**


**Developing holey fibres for evanescent field devices**

T.M. Monro, D.J. Richardson and P.J. Bennett

The overlap of the optical mode in a holey fibre with the air holes is calculated for the first time. This is achieved using a vector modal decomposition approach. It is shown that a significant fraction of the modal power can be made to overlap with the holes, which suggests that these unusual fibres may be useful as evanescent field devices.

**Introduction:** Holey optical fibres (HFs) have a cladding region comprised of air holes running along the full length of the fibre (see Fig. 1). One example of an HF is a photonic crystal fibre (PCF), in which the holes are arranged periodically. HFs guide light due to the effective refractive index difference between the core (a missing hole) and the cladding. Altering the hole arrangement can radically change the properties of HFs, and investigations to date have explored modal profiles, mode area and dispersion [1, 2]. The unusual properties of HFs arise from the strong wavelength dependence of the effective cladding index $n_c$; at longer wavelengths the field extends further into the holes, reducing $n_c$. As a consequence, some HFs can be singlemode regardless of the wavelength [1].

![Fig. 1 SEM of typical large air fill HF](image)

In [2] we developed a scalar orthogonal function method for HFs, which is valid when the holes are small. We have also extended this to the vector case, which enables us to explore the full range of HFs. This technique involves decomposing the modal field using localised functions. The central index defect and the air hole lattice are described independently using localised functions for the defect and periodic functions for the holes. This can be efficient and accurate because the quantities are described by functions chosen carefully to suit. The holes in HFs open up new opportunities for exploiting the interaction of light with gases and liquids via evanescent field effects. For example, the concentration of pollutants in a gas could be determined by measuring the absorption which occurs as light propagates through the gas for a range of wavelengths [3]. We show that the HF geometry can naturally provide extremely long optical path lengths.

**Overlap with holes:** To assess the suitability of HFs for evanescent field devices, it is crucial to know the magnitude of the overlap of the modal field with the holes, and here we present what we believe to be the first such calculations. We define $P_{\text{field}}$, to be the fraction of the fundamental mode's power which is located in the holes. First the mode profile for a given wavelength is calculated using the full vector model. It is then straightforward to evaluate $P_{\text{field}}$ at this wavelength numerically, and we have calculated $P_{\text{field}}$ for a range of different HFs.