value problems for which the solutions are known in a closed form:
(i) the determination of the eigenvalues and of the eigenvectors of the non-dimensional Helmholtz equation [1];
(ii) the evaluation of the characteristic modes for a perfectly conducting circular cylinder with radius \( \lambda /2 \) [5].

**Table 2:** Analytical and numerical eigenvalues for eqn. 1 (problem size \( 12 \times 12 \)) and eqn. 2 (problem size \( 64 \times 64 \))

<table>
<thead>
<tr>
<th>Exact solution (eqn. 1)</th>
<th>Higham-Cheng algorithm</th>
<th>Direct inversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond(A) = 5.96981x10^{-6}</td>
<td>9.86090x10^{10}</td>
<td>-1.36522x10^{-6} - (2.05276x10^{10})</td>
</tr>
<tr>
<td>Cond(B) = 1.90297x10^{-7}</td>
<td>9.86090x10^{10}</td>
<td>1.52723x10^{-6} + (1.89317x10^{10})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exact solution (eqn. 2)</th>
<th>Higham-Cheng algorithm</th>
<th>Direct inversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond(A) = 1.29253x10^{-6}</td>
<td>-1.26000x10^{10}</td>
<td>-3.56120x10^{-6} + (3.21893x10^{10})</td>
</tr>
<tr>
<td>Cond(B) = 5.50606x10^{-7}</td>
<td>-1.26000x10^{10}</td>
<td>4.91550x10^{-6}</td>
</tr>
</tbody>
</table>

Fig. 1a shows the field of values for the pair (A, B) related to the problem (eqn. 1) obtained by discretising the Helmholtz equation using the moment method. Even if the pair is expected to be definite, the discretisation process results in an indefinite pair with \( \gamma = 0 \). Fig. 1b shows the field of values for the pair (A, B) relevant to the problem (eqn. 2) obtained discretising the electrical field integral equation with the method of moments. In this case, the matrix B turns out to be indefinite but the pair is definite because \( \gamma > 0 \). In Table 2 we have compared the analytical eigenvalues against the results obtained with the Higham-Cheng algorithm and with the inversion of the B matrix. As can be seen, in both cases the Higham-Cheng algorithm, even if acting on very ill-conditioned matrices, provides much better results than the direct inversion technique. Finally, it should be pointed out that the Higham-Cheng algorithm introduces additional computational effort for large matrices, although it can be successfully applied whenever the determination of the eigenvalues is problematic because of discretisation errors.

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**Bidirectional erbium-doped fibre amplifier with non-reciprocal optical filter**


A 24dB gain bidirectional erbium-doped fibre amplifier (EDFA) using a new non-reciprocal optical filter is demonstrated. Using the amplifier 2.5Gbit/s × 8 channel WDM signals were transmitted over 160km long singlemode fibre. The measured penalty caused by multiple optical reflection was negligible.

**Introduction:** The wavelength interleaved bidirectional transmission system is attractive since it can reduce not only the number of fibre links, but also the nonlinear effects between adjacent channels [1]. However, the maximum gain of a bidirectional EDFA is limited to ~19dB because of the relative intensity noise (RIN) caused by Rayleigh backscattering [2]. To overcome this problem, bidirectional EDFAs with separated optical paths depending on the direction of light propagation have been proposed, i.e., the bidirectional amplifier was the combination of two unidirectional amplifiers [3, 4]. In this Letter, we demonstrate a simple two-stage bidirectional EDFA with a new non-reciprocal optical filter as an inter-stage component. The filter has different transfer wavelength characteristics with respect to the propagation direction. The proposed amplifier improves the noise figure because it does not require additional optical components such as optical circulators or wavelength division multiplexers to separate the optical path. The amplifier was used for 2.5Gbit/s × 8 channel wavelength interleaved bidirectional transmission over 160km long singlemode fibre. We observed negligible power penalty when the amplifier gain was 24dB.

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**References**


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**Fig. 1**: Configuration of bidirectional EDFA with non-reciprocal filter


Inset: Measured transfer characteristics of non-reciprocal filter

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**Fig. 2**: Experimental results: The configuration of the proposed bidirectional EDFA is shown in Fig. 1. The non-reciprocal optical filter consisted of a conventional polarisation-independent optical isolator and a wavelength-sensitive retardation plate (WSRP). The isolator was composed of two polarisation beam splitters, a non-reciprocal 45° rotator using the Faraday effect, and a reciprocal 45° rotator [5]. A birefringent crystal, 17mm long Calcite, was used for the WSRP. This periodically and reciprocally rotated the polarisation states according to the wavelength of the light. Therefore, the filter provides different periodic transfer functions according to the propagation direction of the light. For example, in the case of the light propagated without polarisation rotation at the WSRP, the filter operates as an isolator, propagating light from left to right, while in the case of 90° rotation, the filter operates as an isolator, propagating light from right to left.

The measured transfer characteristics of the filter are shown in Fig. 1. The insertion loss and the extinction ratio were 1.5 and 16dB, respectively. The filter had a free spectral range (FSR) of...
100GHz and 3dB bandwidth was approximately half the FSR. The offset between the two transfer spectra was 50GHz.

Two 7m long EDFs pumped by 980nm laser diodes were utilised for the bidirectional EDFA. The signal gain of the bidirectional EDFA was 24dB and their noise figure was 5.3dB, when we launched 4-channel signals with an optical power of ~22dBm per channel at each side.

Fig. 2 Experimental setup for bidirectional transmission
BA: bidirectional amplifier, VA: variable attenuator, BPF: bandpass filter

To evaluate the performance of the amplifier, we transmitted wavelength-division multiplexed 8 channel 2.5Gbit/s signals bidirectionally. The experimental setup is shown in Fig. 2. The total transmission length was 160km and the amplifier was located at the centre of the transmission fibre. We adjusted the span loss of each fibre section to 24dB by using variable attenuators. The signals were interleaved with a channel spacing of ~150 or 250GHz. The signal wavelengths were 1547.72, 1550.85, 1554.04 and 1557.23nm (for downstream), and 1549.69, 1552.86, 1555.22 and 1559.19nm (for upstream). The multiplexed signals were modulated at 2.5Gbit/s (pattern length: 2^{23}−1) using two LiNbO₃ modulators. A pin receiver with an optical preamplifier was used to detect the demultiplexed signal.

Fig. 3 Measured optical spectra after transmission over 160km fibre
--- input spectrum of EDFA 3
--- input spectrum of EDFA 4

Fig. 3 shows the measured spectra after transmission. The solid and dotted lines are the input spectrum of EDFA 3 and EDFA 4, respectively. There exist three power levels, the received signal level, the back-scattered signal level, and the filtered ASE noise level from the top. Since the filter reduces injection of the ASE noise generated in one amplifier stage to the other, the maximum achievable output power of signals can be increased.

Fig. 4 shows the measured bit error rate curves of the channel 4 (1552,86nm) before and after transmission. The power penalties of the other channels were less than that of channel 4. The inset shows the excess power penalties of the transmitted signals compared with the unidirectional transmission at a BER of 10⁻⁶. The maximum power penalty due to RIN was less than 0.2dB, which coincided with the theoretical value [2]. The maximum gain of the proposed bidirectional EDFA can be increased by enhancing the isolation of the filter. Recently, another group reported a non-reciprocal filter with an isolation of 45dB [6]. We believe that the maximum allowable gain of the amplifier can be increased up to 40dB.

Conclusion: We have demonstrated a 24dB bidirectional EDFA with 5.3dB noise figure using a non-reciprocal filter that has an isolation of 16dB. Using the amplifier, we transmitted a 2.5Gbit/s × 8 channel WDM signal over 160km of single-mode fibre. The measured power penalty due to multiple optical reflection was less than 0.2dB. The proposed amplifier can be used for long-haul bidirectional WDM transmission systems and networks.

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References

Fabrication of tilted fibre-grating polarisation-dependent loss equaliser

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The fabrication of a polarisation-dependent loss (PDL) equaliser using tilted fibre Bragg gratings in standard telecommunications fibre is demonstrated. The equaliser has a predetermined level of PDL in a specific wavelength range, which is used to compensate for the PDL of a component or system.