approximation of the impulse response than \( \{A_2, b_2, c_2\} \). Further, note that

\[
\|h_1\|_2^2 = 0.1610 \times 10^{-1}
\]

\[
\|h_2\|_2^2 = 0.1591 \times 10^{-1}
\]

and

\[
\|h_3\|_2^2 = 0.1609 \times 10^{-1}
\]

where \( h(t), h_3(t), h_2(t) \) are the impulse response of the original system and the models respectively. As expected from the discussion in Reference 3, Davidson's method gives less error for the impulse response norm than Moore's technique. This example however, shows that simply minimising the error in the impulse response norm, does not necessarily lead to a better approximation of the impulse response.

Consider now the frequency response for the original system and the two reduced order models (Fig. 2). It is clear that \( \{A_1, b_1, c_1\} \) gives a better approximation of the low-frequency behaviour of the original system. This can also be observed by considering the step response of the three systems (Fig. 3). The model \( \{A_3, b_2, c_2\} \) does not approximate the steady-state value of the original system.

The above example and the example in Reference 3 indicate that both techniques\(^3\) can fail to retain the most significant states and, therefore, both the second-order modes and the \( d_i \) should be considered for state truncation.

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**References**


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**BROADBAND DIODE-PUMPED FIBRE LASER**

**Indexing terms:** Lasers and laser applications, Optical fibres, Semiconductor lasers, Fibre optics

We report the observation of a strong dependence of the emission spectrum (centre wavelength and linewidth) of Nd³⁺:silica fibre lasers on pump wavelength. In a particular fibre, careful selection of the pump wavelength has led to the operation of a broadband fibre laser at 1060 nm with 19 nm FWHM bandwidth. When pumped with a 30 mW diode laser, it exhibits a 1 mW threshold, a 2.5 mW output, and an intrinsic average wavelength temperature stability of about 10 ppm/°C.

Miniature broadband optical sources are needed in fibre optic gyroscopes to reduce coherent errors due to backscattering and polarisation crosscoupling.\(^3\) The broadband sources currently employed are superluminescent diodes (SLDs), which generally suffer from relatively low coupling to single-mode fibres,\(^2\) spectrum sensitivity to optical feedback and, more seriously, wavelength sensitivity to temperature.\(^4\) Recently, we reported a new broadband source made of a superfluorescent Nd³⁺:silica fibre laser, which exhibits improved characteristics over an SLD, including a ten-fold increase in spectrum stability with temperature.\(^5\) However, at this point in time it still requires a high threshold pump power which cannot be provided by currently available long-lifetime diode lasers.

In this letter, we report the observation of a strong dependence of the spectrum of Nd³⁺: silica fibre lasers on the excitation wavelength. This observation has led to the development of a new type of broadband fibre laser which utilises the inhomogeneous nature of the electronic transitions

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*WILSON, K.: Litton Guidance and Control, private communication*
of this material.\textsuperscript{3,5} When excited several times above threshold, such a laser can emit a spectrum which covers a significant fraction of the fluorescence spectrum. Applied to Nd\textsuperscript{3+}: silica fibre lasers, this approach has produced a low-threshold, 19\,nm bandwidth source.

The fibre involved in this work, manufactured by British Telecom Research Laboratories (BTRL), has a 6\,µm diameter core doped with about 0.03\% of Nd and 1 mole \% of P\textsubscript{2}O\textsubscript{5}.\textsuperscript{3} The LP\textsubscript{01} mode cutoff wavelength is 920\,nm. Fibre lasers were made by bonding 500\,µm-thick dielectric mirrors onto the polished ends of a fibre, whose length ranged between 2 and 16\,m (giving essentially the same spectral characteristics). One of the mirrors was a high reflector (HR) and the other a 90\% reflector, near the 1.06\,µm laser wavelength. It was optically end-pumped with either a CW Styryl 9 dye laser, tunable between 790 and 850\,nm, or a diode laser, which emitted up to 30\,mW at 830\,nm. The pump beam was focused with a \times 20 objective lens and coupled to the fibre through the HR, which transmitted 81\% of the pump power. The coupling efficiency into the fibre (including mirror backreflection) was typically 55\% and 25\% for these two pump sources, respectively.

The evolution of the fibre laser output spectrum with pump wavelength ($\lambda_p$) is shown in Fig.\,1. All spectra were measured at the same pump power, with a 0.5\,nm resolution spectrophotometer. For $\lambda_p$ between 804 and 815\,nm, the spectrum is relatively narrow and shifts to longer wavelengths as $\lambda_p$ is increased. The FWHM linewidth remains under 6.5\,nm, even far above threshold. For $\lambda_p$ > 815\,nm, the laser spectrum is much broader and covers most of the narrowband tuning range (see Fig.\,1). At threshold, the spectrum consists of two separate, narrower peaks about 10\,nm apart. Slightly above threshold, and at higher pump power, the spectrum evolves to the typical shape shown in Fig.\,1. Its general shape, in particular the relative magnitude of the central dip, does not vary significantly for 818\,nm < $\lambda_p$ < 835\,nm.

All spectra were found to exhibit some fine structure (\approx 1-2\,nm period, 30-50\% depth) superimposed to the general spectra of Fig.\,1 (not shown for clarity). The origin of this modulation is primarily feedback from the outer surfaces of the reflectors, a mechanism to which the spectrum of Nd\textsuperscript{3+}: silica fibre lasers is fairly sensitive.\textsuperscript{5} The modulation depth was reduced below 10\% by using thicker mirrors, thereby reducing the magnitude of the feedback. Similar results were obtained by polishing the reflector outer surfaces at a 15\,° angle. The remaining structure may arise from either residual backreflection or competition between the large number of longitudinal modes supported by the laser cavity. In the former situation, depositing the mirrors directly onto the fibre ends would probably eliminate this structure.

The pump wavelength dependence has been attributed to site-dependent pumping. The transitions of Nd\textsuperscript{3+} in multi-component glasses can be strongly inhomogeneously broadened as a result of the multiplicity of atomic sites available to the ions.\textsuperscript{4} Site-dependent pumping implies that ions residing in certain sites (and also emitting around a specific wavelength) are preferentially excited by narrowband pumping at a particular wavelength. This dependence, as well as the general features of the spectrum,\textsuperscript{6} are therefore expected to depend on the nature and concentration of the codopants present in the core, as observed qualitatively with fibres from other manufacturers. The broader emission is believed to be due to the excitation of multiple Nd\textsuperscript{3+} sites. Our observations indicate that a broader emission occurs when $\lambda_p$ lies away from the centre of the 810\,nm absorption band of the material (see spectra at $\lambda_p$ = 793.7 and 818\,nm in Fig.\,1). It is speculated that under such conditions the excitation of multiple Nd\textsuperscript{3+} sites takes place through (site-dependent) absorption tails belonging either to the same band or to adjacent bands (e.g. the 810 and 870\,nm bands of Nd\textsuperscript{3+}), or through cross-relaxation between upper laser levels.

A typical output power against absorbed pump power curve, measured with the dye laser tuned near 822\,nm as the pump source, is shown in Fig.\,2. The absorbed pump power required to reach threshold is about 1.3\,mW. The output power grows essentially linearly with absorbed pump power, as expected, with a slope efficiency approaching 60\%. Similar results were observed when tuning $\lambda_p$ between 808 and 822\,nm. With the 30\,mW diode laser, the threshold was about 1\,mW and the maximum output power 2.5\,mW. Fig.\,3 shows the evolution of the linewidth in the broadband regime ($\lambda_p$ = 818\,nm) as the pump power is increased. Near threshold the spectrum linewidth is 10\,nm. As the excitation level is increased, the linewidth broadens, as expected in an inhomogeneously-broadened laser, and rapidly reaches an asymptotic value close to 19\,nm. Consequently, under normal pumping conditions, the linewidth is relatively immune to pump power variations.

The two main contributions to the temperature sensitivity of the spectrum are the dependence on temperature (i) of the emission wavelength of the laser material, and (ii) of the diode laser pump wavelength (as the emission wavelength depends on $\lambda_p$, typically 300 ppm/°C.\textsuperscript{4} For gyroscope applications, the parameter of interest is the average emission wavelength $\langle \lambda \rangle = \int I(\lambda) \, d\lambda / \int I(\lambda) \, d\lambda$, where $I(\lambda)$ is the spectrum intensity.
Measurements performed with the fibre laser indicate that for a few pump wavelengths (about 802, 815 and 822 nm), the dependence of $\beta$ on $\Delta$ (contribution (ii)) locally vanishes. At this wavelength the stability of $\beta$ should approach the intrinsic material stability (contribution (i)), measured to be on the order of 10 ppm/°C, making this source about 30 times less temperature sensitive than a typical SDL.*

In conclusion, it has been found that the wavelength at which an Nd:SiO$_2$ fibre laser is pumped can have a significant effect on the laser spectrum centre frequency and line-width. By proper selection of the pump wavelength, we have developed a low-threshold fibre laser which efficiently converts diode laser power into a broadband emission (19 nm), with an average wavelength emission stability on the order of 10 ppm/°C.

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LARGE ELECTROABSORPTION EFFECT IN GaInAs/InP MULTIPLE QUANTUM WELL (MQW) OPTICAL MODULATOR GROWN BY OMVPE

Indexing terms: Optical modulation, Modulators, Quantum optics, Semiconductor growth

TO make short, high-speed electroabsorption modulators, it is necessary to use a material and device structure that displays a large change in absorption coefficient, $\Delta$. We report a device with $\Delta = 7800 \text{ cm}^{-1}$, which provides an on/off ratio of 44:1 at $\lambda = 1.6 \mu m$ with a drive voltage of 10 V.

High-speed electroabsorption optical modulators must be short, to keep the device capacitance small. To make short high-contrast devices, it is necessary to make use of materials with a large electric-field induced change in the absorption coefficient, $\Delta$. Because of their large electroabsorption effect, GaAs/AlGaAs multiple quantum wells (MQWs) have proved to be useful as the active medium in modulators. At a wavelength of $\lambda = 0.86 \mu m$, $\Delta = 15000 \text{ cm}^{-1}$ has been observed. To date, the modulators operating near $\lambda = 1.55 \mu m$ have operated with fairly small $\Delta$. In this letter, we report a GaInAs/InP MQW modulator which demonstrates an $\Delta = 7800 \text{ cm}^{-1}$ with a drive voltage of only 10 V. To our knowledge this is the largest $\Delta$ observed to date at long wavelength. We also used optical fibre micro-lenses to couple in and out of the device, to demonstrate a true fibre-coupled device.

Assuming no light leakage around the waveguide, the on/off ratio of a waveguide electroabsorptive modulator of length $L$ is given by

$$ R = \exp \left( \frac{\Gamma \Delta L}{\Delta} \right) $$

where $\Gamma$ is the overlap between the quantum wells and the optical mode of the slab waveguide. It is important to use a material with large $\Delta$ in an electroabsorptive modulator so that a large $R$ can be obtained with a value of $L$ short enough that high speeds can be reached.

A number of material systems have been demonstrated for long-wavelength modulators. Bulk electroabsorption has been demonstrated in GaInAsP with a $\Delta = 150 \text{ cm}^{-1}$. In GaInAs/AlInAs MQWs grown by molecular beam epitaxy (MBE), a $\Delta = 690 \text{ cm}^{-1}$ was reported. GaSb/AlGaSb MQWs grown by MBE were shown to display $\Delta = 5500 \text{ cm}^{-1}$ with a drive voltage of only 2.7 V in a waveguide device. However, this material system is not as easy to process as the GaInAs-based material. Recently there has been significant progress in MQW modulators made with the GaInAs/InP system. Using MQWs grown by organometallic vapour phase epitaxy (OMVPE) a $\Delta = 2600 \text{ cm}^{-1}$ was observed for light propagating perpendicular to the wafer, but a waveguide device in this material was designed to be operated with light well below the bandgap of the MQWs, so only a $\Delta = 640 \text{ cm}^{-1}$ was observed. This waveguide device did, however, display a very low insertion loss of 2.9 dB. Both of these devices had a drive voltage of 20 V. Finally, a waveguide device grown by metalorganic molecular beam epitaxy (MOMBE) with $\Delta = 400 \text{ cm}^{-1}$ at a drive voltage of 5 V has been reported.

Our device is shown schematically in Fig. 1. A set of ten GaInAs quantum wells, each 70 Å thick, was grown in the centre of the 0.62 μm thick undoped region of a pin diode by OMVPE. This was, in turn, in the centre of a 1.4 μm thick superlattice slab waveguide made from alternating layers of 180 Å of InP and 20 Å GaInAs. The relatively low number of wells and the thin undoped region allow us to minimise the drive voltage and the electric field inhomogeneity in this device. A single layer antireflection coating of SiO$_2$ was applied to both cleaved facets. By numerically solving the wave equation, we estimate that the full width at the 1/e point of the mode of the single-mode waveguide is 1.75 μm. We will see below that efficiently launching into such a small mode is difficult. By operating with a moderate $\Gamma = 64\%$ and a short device length of $L = 76 \mu m$, we are able to operate fairly close

Fig. 1 Schematic view of waveguide GaInAs/InP MQW modulator