the PD is obtained. This value will be increased by a factor of 1.8 when using ARC. Other published articles on silicon receivers [5,6] reported data rates of 300 and 370 Mbit/s using supply voltages of 8V, 30V, and ±3V, 10V for the preamplifier and photodetector, respectively. In our case only one power supply of 3.3V for the photodiode and the preamplifier is necessary. The power consumption of the OEIC is 17mW.

**Table 1:** Rise and fall times of receiver against doping concentration \( C_r \)

<table>
<thead>
<tr>
<th>( C_r ) [cm(^{-2})]</th>
<th>( 10^{13} )</th>
<th>( 10^{14} )</th>
<th>( 5 \times 10^{13} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_r ) [ns]</td>
<td>15.5</td>
<td>0.77</td>
<td>0.65</td>
</tr>
<tr>
<td>( t_f ) [ns]</td>
<td>17.6</td>
<td>1.16</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**Measurement and results:** pin PDs and OEICs were fabricated using a 1.0µm CMOS technology. The measurements were carried out at wafer level. A red laser (\( L = 638.3\) nm) was modulated by an ECL pattern generator and the light was coupled into the pin photodiode via a singlemode fibre. The output signal of the receiver was measured with a picoprobe and a digital sampling oscilloscope. In Table 1 the measured rise and fall times of the OEICs are shown, with the dependence of the doping concentration \( C_r \). These values are not corrected corresponding to the rise and fall times of the oscilloscope, picoprobe and laser, respectively.

![Fig. 3](image)

**Fig. 3** High-speed receiver eye diagrams for different doping concentrations of epitaxial layer with \( V_{DD} = 3.3V \)

Incident optical power was constant

- Time: 500 ps/div, amplitude: 0.14 V/div
- \( a \ C_r = 1 \times 10^{14} \) cm\(^{-2}\)
- \( b \ C_r = 1 \times 10^{15} \) cm\(^{-2}\)
- \( c \ C_r = 5 \times 10^{15} \) cm\(^{-2}\)

As can be seen, the biggest improvement is already made between the standard concentration \( C_r = 10^{14} \) cm\(^{-2}\). This indicates that the depletion region spreads through the whole epitaxial layer and slow carrier diffusion in the PD is eliminated. This is also verified by the eye diagrams in Fig. 3: the eye diagrams for the concentration of \( 10^{14} \) cm\(^{-2}\) and \( 5 \times 10^{15} \) cm\(^{-2}\) show a sufficiently wide open eye at a bit rate of 622 Mbit/s in the nonreturn-to-zero (NRZ) mode, using a pseudorandom bit sequence (PRBS) of 2\(^{31}-1\). Device and circuit simulations show that this bit rate is also possible for longer wavelengths (780 and 850nm).

Results for \( C_r = 2 \times 10^{15} \) cm\(^{-2}\) showed that rise and fall times of the CMOS-integrated pin PDs of 0.19 and 0.24ns, respectively, are achievable [7]. These values correspond to a data rate of 1.5 Gbit/s for the pin PD, using the estimation \( BR = 2[(BL+1)/BL] \). Thus, the highest possible data rate of the OEIC in 1.0µm CMOS-technology is limited by the preamplifier. With submicrometre receiver OEICs, therefore, a data rate in excess of 1Gbit/s seems to be possible.

**Conclusions:** A new integration method for a vertical pin photodiode in a twin-well CMOS process has been developed. A bit rate of 622 Mbit/s with a 3.3V single power supply was demonstrated with receiver OEICs in 1.0µm CMOS technology using different epitaxial doping concentrations up to \( 10^{14} \) cm\(^{-2}\). Even higher bit rates will be feasible for submicrometre CMOS technologies.

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**References**


**Dual numerical aperture confocal operation of moving fibre bar code reader**

D.A. Roberts, R.R.A. Symx, A.S. Holmes and E.M. Yeatman

A compact bar code reader using pre-lens scanning by a piezoelectrically-activated vibrating optical fibre cantilever is demonstrated. Dual numerical aperture confocal operation, based on transmission of a guided mode and reception of cladding modes, is shown to be a simple method for increasing and separating the return signal.

Information acquisition by optical scanning is a powerful technique with applications in a range of markets. Bar code scanners are indispensable in the retail industries [1] and more advanced applications include ophthalmic scanners for retinal imaging [2] and confocal microscopy [3].

Many systems perform scanning using rotating polygon mirrors and holographic lenses [4], or galvanom- driven torsion mirrors [1]. Consequently, they are bulky and fragile. Miniaturisation using wafer scale technology will reduce cost and increase applications, for example by allowing an operator to wear a finger-mounted scanner [5]. Microengineering methods are now being applied to scanners, and King et al. have demonstrated surface micromachined polysilicon torsion mirrors with a scan angle of 28° [6].

An alternative system with potential for miniaturisation uses a moving fibre or waveguide. Light emerging from the fibre is
imaged to a spot by a lens, and a small displacement of the fibre tip is magnified to produce a scan line in the image plane. This displacement is generated by exciting the fundamental resonance of a fibre cantilever using, for example, piezoelectric actuation [5].

An unfortunate consequence of miniaturising a scanner without simultaneously reducing the focal distance is that the return power decreases as the square of the system dimension. It is therefore important to devise architectures that maximise the optical signal. In conventional systems, performance is optimised by using receiver optics with a larger numerical aperture (NA) than the transmission optics, confocal detection, and narrow band optical filtering [4]. Here we describe a fibre optic resonant scanner (FORS), which uses dual NA confocal operation and optical filtering to obtain good performance from a layout suitable for eventual integration on V-grooved Si. The same principles could be used in a fully integrated device.

![Fig. 1 Confocal fibre optic resonant scanner](image)

- Guided mode detection
- Cladding mode detection

Fig. 1a shows the initial layout of the FORS, which consists of a 1mW 635nm laser (LD), an unjacketed length of single mode fibre mounted on a piezoelectric transducer, a graded index lens (GRIN), a beamsplitter (BS) and a detector (PD). Light from the fibre is imaged by the lens, the parameters of which are chosen for a compromise between magnification and resolution; greater magnification gives a longer scan, but a larger spot. A quarter pitch lens with a 2mm aperture and an NA of 0.37 was used; this gives a magnification of 75 at an image distance of 200mm. Antireflection coating provided out-of-band signal rejection.

Scanning is achieved by exciting the fundamental mode of the fibre. The resonant frequency is \( f = \frac{1}{2\pi} \sqrt{\frac{L}{2EIP^2b_0}} \), where \( L \) is the length of the fibre cantilever, \( E \) and \( P \) are Young’s modulus and the density of silica (7.17 \times 10^3 Nm^2 kgm⁻³ respectively), and \( d = \frac{m^2}{2} \) and \( m = \frac{n^2}{2} \) are the area and second moment of area for a cylinder of diameter \( d \). The fibre had a diameter of 125nm, an NA of 0.12 and a mode field diameter of 4.0um at 630nm, giving a 300um diameter spot at an image distance of 200mm.

![Fig. 2 Photograph of experimental device](image)

Calculations show that the resonance is between 3.6kHz and 225kHz for cantilever lengths between 5 and 20mm. A 12mm diameter Kingstate KPE165 piezoelectric transducer with a nominal resonant frequency of 4.8kHz was used, but the output was sufficiently broadband to drive cantilevers up to 20mm long. For a 20V peak-to-peak sinusoidal drive, peak displacements of ~80μm were achieved using long cantilevers, giving a scan length of ~120mm at an image distance of 200mm and a correspondingly reduced scan at shorter distances.

The performance of the FORS was assessed by reading standard Code 2 of 5 barcodes on plain paper. Backscattered light was collected using the GRIN lens, and coupled back into the fibre. Early experiments showed that the signal output intensity was limited by the low NA of the fibre. However, the return power can be increased by discarding this signal, and detecting the power in the cladding modes instead. These may be separated by a mode stripper without the need for a beam splitter (Fig. 1b), further enhancing the signal.

![Fig. 3 Frequency response of peak fibre tip displacement at different drive voltages](image)

Length of fibre cantilever: 19mm

![Fig. 4 Return signals obtained by two methods](image)

(i) Dual NA confocal operation
(ii) Separate collector

Since the received power depends on the square of numerical aperture, the maximum signal enhancement obtained by this approach is \( G = \frac{4}{\eta_1^2 (NA_f)^2} \) where the subscripts \( L \) and \( F \) refer to lens and fibre, and the factor of 4 arises from discarding a double pass through a 50:50 splitter (the optimum). With the experimental parameters here, \( G = 34 \) (or 15.3dB). Higher values could be obtained with a lens of higher NA. The fraction of return power passing the lens that may be collected from the cladding is \( \eta = \frac{NA_f^2}{NA_f^2} \). Here, \( \eta = 89.3\% \), although this fraction would also rise with an increase in \( NA_f \).

To implement this strategy, the cladding was bonded using index matching epoxy to a 7mm² Siemens BPW345 Si surface-mount detector attached to the transducer. Fig. 2 shows the experimental system, and Fig. 3 the frequency variation of the tip displacement of a 19mm long fibre cantilever at different drive voltages. Sharp resonances are displayed, with a Q-factor of ~130.

This system had a greatly improved signal output compared with that in Fig. 1a. Fig. 4 shows raw signals recovered from moving test targets at a fixed focal distance by (i) the mode-stripping detector, and (ii) a similar adjacent reference GRIN lens and detector. The amplitude of the former signal is ~65% of the latter, demonstrating efficient light collection. After filtering and regeneration, signals were passed to an HP HBCR-1611 bar code decoder.
Jones vector representing the input state of polarisation, \( \varphi \) is the optical frequency and \( A \) is the complex amplitude of the field. Using Jones’ formulation, the output field is given by:

\[
E_{\text{out}} = T(\varphi)E_{\text{in}}
\]

where \( T(\varphi) \) is a frequency-dependent \( 2 \times 2 \) complex matrix \([4]\). In realistic optical transmission media \( T(\varphi) \) often possesses a complex frequency dependence. Therefore, to investigate the dispersive properties of the medium, it is useful to expand \( T(\omega) \) near the carrier frequency \( \omega_0 \) in powers of \( \varphi - \omega_0 \). In conventional analysis of pulse propagation in dispersive, isotropic media it is customary to represent the frequency dependent phase acquired by the propagating wave by its Taylor expansion near \( \omega_0 \), rather than expanding the field itself. To generalise this to the non-isotropic case, we propose the following expansion of the medium Jones matrix:

\[
T(\omega + \Omega) = T_0 + \Omega T_1 + \frac{1}{2!} \Omega^2 T_2 + \cdots
\]

where \( \Omega \ll \omega_0 \), \( T_0 = T(\omega_0) \) and the parameters denoted by \( N_k \) (\( k = 1, 2, 3, \ldots \)) are \( 2 \times 2 \) complex matrices which can be found by successively differentiating eqn. 1 with respect to \( \Omega \) and substituting \( \Omega = 0 \). The first two terms in the expansion are given by:

\[
N_1 = T_0^{-1}T_1, \quad N_2 = T_0^{-1}T_2 = (N_1)^2
\]

Here the primes denote differentiation with respect to frequency. It can be easily seen that as long as \( T(\omega_0) \) is non-singular (i.e. the system does not contain an ideal polariser) and differentiable \( M \) times, then \( N_k \) will be well defined for \( k = 1, 2, 3, \ldots, M \). We denote the eigenvectors and eigenvalues of \( N_k \) as \( \xi_{k\pm} \) and \( \alpha_{k\pm} \), respectively. The eigenvectors of \( N_1 \), \( \xi_{k\pm} \), were shown to be the input PSPs of the medium and the imaginary part of \( (\alpha_{k+} - \alpha_{k-}) \) is the DGD associated with them \([5]\). We now utilise the well-known theorem that if \( A \) is a non-singular matrix with eigenvalues \( \alpha_k \), then \( e^{A} \) and \( A \) have the same eigenvalues, and the eigenvalues of \( e^{A} \) are \( e^{\alpha_k} \). Therefore:

\[
T(\omega + \Omega) = T_0 + T_1\xi_{k\pm}P_{k\pm}^{-1} + \cdots
\]

where

\[
P_k \equiv [\xi_{k+}, \xi_{k-}] \quad \text{and} \quad Q_k \equiv \begin{bmatrix} e^{i\Omega\alpha_{k+}} & 0 \\ 0 & e^{i\Omega\alpha_{k-}} \end{bmatrix}
\]

The main advantages of this representation is that it enables us to consider the effects of the different orders of PMD separately and that high-order terms have the same form as the first-order term. Each order of PMD is represented as a separate optical system with eigenstates \( \xi_{k\pm} \) and eigenvalues \( \alpha_{k\pm} \). We refer to the parameter denoted by \( \xi_{k\pm} \) as the input principal states of polarisation of the \( k \)-th order and to the difference between the imaginary parts of \( \alpha_{k+} \) and \( \alpha_{k-} \) as the differential group-delay dispersion (DGD) of the \( k \)-th order.

**First-order PMD:** eqn. 3 can be used to study the propagation of short pulses in a polarisation dispersive transmission medium. Let \( A(t) \) and \( A(\Omega) \) describe the amplitude of an optical field at the input of the transmission medium and the corresponding Fourier transform, respectively. We consider first the case where only the zero and first-order terms in eqn. 3 are significant. The output field in this case is given by:

\[
E_{\text{out}}(t) \approx \frac{1}{2\pi} \int_{-\infty}^{\infty} A_f(\Omega) e^{i(\omega_0 + \Omega)t} T_0 P_1 Q_1(\Omega) P_1^{-1} \text{cos} \Omega t \, d\Omega
\]

In the absence of polarisation dependent loss or gain (PDL/G) \( T(\omega) \) is proportional to a unitary matrix. In this case \( \alpha_{k\pm} \) are purely imaginary and integration of eqn. 5 yields:

\[
E_{\text{out}}(t) = \begin{bmatrix} c_{k+} A(t - \alpha_{k+}) \\ -c_{k-} A(t - \alpha_{k-}) \end{bmatrix} e^{i\varphi_{\text{out}}}
\]

where \( c_{k\pm} \) are defined by \( [c_{k+}, c_{k-}] = P_1^{-1} \xi_{k\pm} \) and \( \text{Im}(\alpha_{k\pm}) \) and \( E_{\text{out}}(t) \) is given by:

**Representation of second-order polarisation mode dispersion**


A new expansion for the Jones matrix of a transmission medium is used to describe high-order polarisation dispersion. Each term in the expansion is characterised by a pair of principal states and the corresponding dispersion parameters. With these descriptors, a new expression for pulse deformation is derived and confirmed by simulation.

**Introduction:** Polarisation mode dispersion (PMD) in singlemode fibres has been extensively studied in recent years. The first-order effects of PMD are conveniently described in terms of the principal states of polarisation (PSPs) and their differential group delay (DGD) \([1]\). Second-order effects of PMD arise from the variation of these descriptors with optical frequency \([2, 3]\). Like chromatic dispersion, the effect of second-order PMD becomes increasingly important as the transmission bandwidth increases. It is thus important to have a simple method for representing and characterising the effects of second-order PMD. Until now, the analysis of second-order PMD was based on expanding the Jones matrix of the transmission medium near the carrier frequency using a Taylor series or by considering the variations of the PMD-vector on the Poincaré sphere. In this Letter we propose a new description of PMD which is based on an exponential expansion of the Jones matrix of the transmission medium. According to this description, different orders of PMD are treated separately as different subsystems and the overall behaviour of the transmission medium is obtained from serially concatenating these systems. Generalising Poole and Wagner’s phenomenological approach \([1]\), each subsystem is described in terms of a pair of principal states and the corresponding dispersion parameters. With the use of this simple model a new expression for pulse deformation due to second-order PMD is derived. The validity of the model is confirmed using an exact numerical simulation.