## Planar lightwave circuit dispersion equaliser module with polarisation insensitive properties

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*Indexing terms: Integrated optics, Equalisers, Light interferometers, Optical polymers*

The authors report the fabrication of an integrated-optic dispersion equaliser module based on a planar lightwave circuit (PLC). The equaliser consists of five asymmetrical Mach-Zehnder interferometers cascaded in series. Polyimide half waveplates inserted in the interferometers eliminate the polarisation dependent path length differences of the equaliser.

*Introduction:* The transmission distance in optical fibre communication systems has been greatly increased by the development of erbium-doped fibre amplifiers [1]. As a result, the main factor limiting the transmission distance when operating at multigigabit data rates is now chromatic dispersion. Several techniques have been reported with which to compensate for the dispersion. They employ nonlinear optical effects in fibres and linear optical dispersion equalisers [2]. A planar lightwave circuit dispersion equaliser reported by the authors offers design flexibility and high tolerance [3–6]. The dispersion of this equaliser can be adjusted to both positive and negative values [3] by using thermo-optic (TO) phase control in silica optical waveguides [7]. The effectiveness of the equaliser has been demonstrated in a 2.5Gbit/s transmission experiment [4]. It was also confirmed that the equaliser can be applied to a 10Gbit/s multichannel transmission system by exploiting its frequency periodicity [5]. The operational frequency range of the equaliser can be doubled by using an amplitude flattening circuit (AFC) with no detrimental effect on the delay characteristics [6].

There is a stress-induced birefringence in PLC devices, which is caused by the difference between the thermal expansion coefficients of the silicon substrate and the silica glass layers [7]. The typical birefringence $B$ is $\sim 10^{-4}$ [7]. The frequency characteristics of the equaliser are shifted by $\Delta f = -(f_{TE}/n_{eff})\cdot B$ for the TE and TM polarisation modes, where $f_{TE}$ is the centre frequency of the operational range for the TE mode and $n_{eff}$ is the refractive index of the core. Therefore, polarisation dependence should be eliminated in practical optical communication systems.

In this Letter, we report a PLC dispersion equaliser module with polarisation insensitive properties. A simple and low loss TE/TM mode conversion method using polyimide half waveplates [8,9] is used to eliminate the polarisation dependence. Fibre pigtails with SC optical connectors are connected to the device by UV curable adhesive. The equaliser is fabricated by using five Mach-Zehnder interferometers with asymmetrical arms cascaded in series. The operational frequency range is 27.5GHz with a dispersion value of 201 ps/nm.

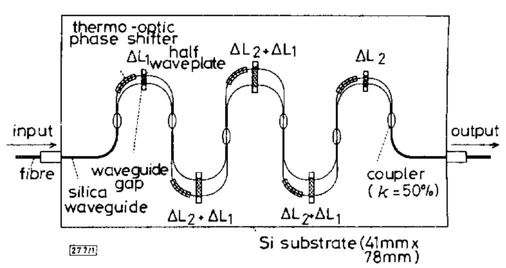


**Fig. 1** *Configuration of PLC dispersion equaliser module with polyimide half waveplates and fibre pigtails*

Relative index difference = 0.75%, core size = 7.0 µm², loss (fibre-to-fibre) = 7.1dB, and $\Delta L_1 = \Delta L_2 = 1.871$ mm

*Design and fabrication:* The configuration of the PLC dispersion equaliser module is shown in Fig. 1. It is composed of five asymmetrical Mach-Zehnder interferometers. We confirmed that the lower and higher frequency components, $f_L = f_0 - W/2$ and $f_H = f_0 + W/2$, pass mainly through the shorter and longer interferometer arms, respectively. Here, $f_0$ is the centre frequency of the operational range and $W$ is typically several tens of gigahertz [3,10]. Thus positive dispersion can be achieved whose inclination is opposite to that of 1.3µm zero-dispersion fibre at 1.55µm. It is possible to adjust both the positive and negative dispersion values by appropriately setting the phase shift differences between the two arms of the interferometers [3]. The device is fabricated with a silica optical waveguide by flame hydrolysis deposition (FHD) and reactive ion etching (RIE) [7]. A chromium heater is deposited on the asymmetrical arms to provide TO phase control [7].

Polyimide half waveplates are inserted into waveguide gaps in the centre of all five interferometers as shown in Fig. 1 [8,9]. The waveplate thickness is ~15µm and the loss increase caused by inserting one waveplate is 0.2–0.3dB. The principal axis directions of the waveplates are inclined at 45° to the waveguide plane for the TE/TM mode conversion [9]. This means that the optical path lengths for TE and TM polarisation modes are equal.

Dispersion-shifted fibre pigtails with SC optical connectors were connected to the input and output waveguides of the device using UV curable adhesive [11]. A Peltier device and heatsink were also installed to provide temperature control. High levels of optical performance such as high temperature stability have been reported in PLC modules with fibres [11]. Fig. 2 shows a photograph of the PLC dispersion equaliser module.

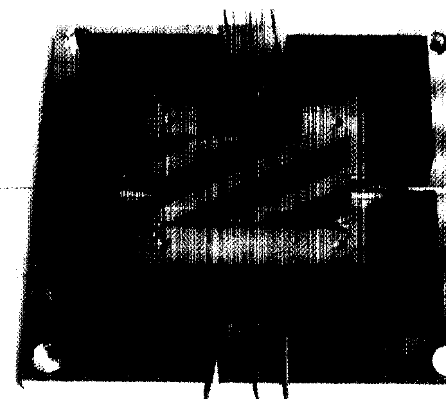

**Fig. 2** *Photograph of PLC dispersion equaliser module*

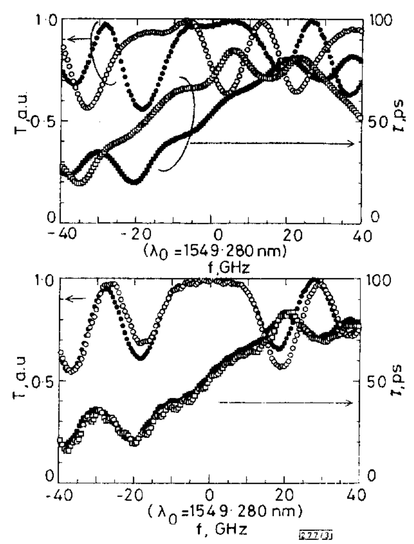


**Fig. 3** *Measured characteristics of PLC dispersion equaliser (positive dispersion)*

Dispersion equalisers (*a*) before and (*b*) after polyimide half waveplate insertion. Filled and unfilled symbols show TE and TM mode characteristics, respectively. Circles and squares indicate power transmittance $T$ and relative delay $\tau$, respectively, against relative frequency $f$

*Measurement:* Fig. 3*a* and *b* show measured characteristics of the PLC dispersion equaliser before and after the half waveplate insertion, respectively. The measurement technique was reported in [12]. Without the waveplates there is a difference of 14.9GHz between the centre frequencies of the TE and TM modes because of the birefringence as shown in Fig. 3*a*. This frequency difference corresponds to a birefringence $B$ of $1.1 \times 10^{-4}$. In Fig. 3*b*, it can be clearly seen that the waveplates have almost completely eliminated the frequency difference. When the half waveplates are inserted, the centre frequency is located between the centre frequencies of the TE and TM modes. However, the phase control of the equaliser was further employed to return the centre wavelength to 1549.280nm. The operational frequency range of the equaliser, which is defined by its 1dB down power transmittance, is 27.5GHz with a dispersion of 201ps/nm.

The fibre-to-fibre device loss is 4.8dB. The loss increase is 1.6dB after waveplate insertion. Therefore, the loss increase for the insertion of one waveplate is estimated to be 0.32dB. The loss increased by 0.7dB after connecting the fibre pigtails. This resulted in a total module loss of 7.1dB.

*Conclusion:* We have fabricated a PLC dispersion equaliser module using dispersion-shifted fibre pigtails with SC optical connectors. The polarisation properties of the equaliser were eliminated by inserting polyimide half waveplates in the centre of the interferometers. The operational frequency range is 27.5GHz with a dispersion of 201ps/nm.

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**References**

1 BERGANO, N.S.: 'Undersea lightwave communications systems using erbium-doped fibre amplifiers' Proc. OEC'94, 1994, (Chiba, Japan), Paper 15C1-1, pp. 366–367
2 JOPSON, R.M.: 'Dispersion control in long high-dispersion fibre links', Proc. ECOC '94, 1994, (Firenze, Italy), Paper We.B.3.1, pp. 675–680
3 TAKIGUCHI, K., OKAMOTO, K., SUZUKI, S., and OHMORI, Y.: 'Planar lightwave circuit optical dispersion equalizer', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 86–88
4 TAKIGUCHI, K., OKAMOTO, K., and MORIWAKI, K.: 'Dispersion compensation using a planar lightwave circuit optical equalizer', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 561–564
5 HAGIMOTO, K., KATAOKA, T., SANO, A., YAMABAYASHI, Y., TAKIGUCHI, K., OKAMOTO, K., and KAWACHI, M.: 'Penalty free dual-channel 10Gbit/s transmission over 132km standard fibre using a PLC delay equaliser with –830 ps/nm'. Proc. OFC'94, San Jose, USA, 1994, Paper PD24, pp. 112–115
6 TAKIGUCHI, K., and OKAMOTO, K.: 'Planar lightwave circuit dispersion equaliser with a wide operational frequauency range', *Electron. Lett.*, 1994, **30**, pp. 1404–1406
7 KAWACHI, M.: 'Silica waveguides on silicon and their application to integrated-optic components', *Opt. Quantum Electron.*, 1990, **22**, pp. 391–416
8 ANDO, S., SAWADA, T., and INOUE, Y.: 'Thin, flexible waveplate of fluorinated polyimide', *Electron. Lett.*, 1993, **29**, pp. 2143–2144
9 INOUE, Y., OHMORI, Y., KAWACHI, M., ANDO, S., SAWADA, T., and TAKAHASHI, H.: 'Polarization mode converter with polyimide half waveplate in silica-based planar lightwave circuits', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 626–628
10 OZEKI, T.: 'Optical equalisers', *Opt. Lett.*, 1992, **17**, pp. 375–377
11 HIBINO, Y., HANAWA, F., NAKAGOME, H., TAKATO, N., MIYA, T., and YAMAGUCHI, M.: 'High reliability silica-based PLC 1×8 splitters on Si', *Electron. Lett.*, 1994, **30**, pp. 640–641
12 RYU, S., HORIUCHI, Y., and MOCHIZUKI, K.: 'Novel chromatic dispersion measurement method over continuous gigahertz tuning range', *J. Lightwave Technol.*, 1989, LT-7, pp. 1177–1180

## Reduced bandwidth optical digital intensity modulation with improved chromatic dispersion tolerance

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*Indexing terms: Electro-optical devices, Lithium niobate, Optical modulation*

A simple optical modulation scheme using a lithium niobate Mach-Zehnder modulator driven by a three level drive waveform is proposed. The two-level intensity modulated (IM) optical signal obtained possesses a smaller optical bandwidth and thus greater chromatic dispersion tolerance compared with existing two-level IM methods used for high data rate transmission (e.g. 10Gbit/s).

*Introduction:* At high bit rates the effect of chromatic dispersion in standard singlemode fibre (SSMF) becomes an increasingly difficult problem when using the 1550nm wavelength window [1]. Examples of methods commonly proposed for overcoming the problem include dispersion compensation [2] in which the overall dispersion of the optical path is reduced to a tolerable amount by equalising the fibre delay characteristics, and pre-chirp [3] in which the transmitted signal is phase or frequency modulated in such a way as to cancel or partially cancel the phase distortion produced by chromatic dispersion.

An alternative method is to use a modulation format which results in a narrower optical spectrum. An example of this is duobinary signalling [4]. Because the phase distortion caused by chromatic dispersion increases rapidly with spectral width, this can be a powerful technique for increasing the tolerance of the system to dispersion. Unfortunately, techniques reported to date [4, 5] which use this principle also possess one or more disadvantages including nonstandard optical signal format, complicated transmitter or receiver structures and intrinsically poor sensitivity.

*Description of method:* The new method relies on the electrical to optical (E/O) conversion properties of a low chirp ($\alpha = 0$) Mach-Zehnder modulator biased about the point of maximum extinction. The optical carrier is nulled and suppressed carrier amplitude modulation results in this region of operation. Because the E/O conversion is reasonably linear, the spectral properties of the drive waveform are transferred to the optical frequency.

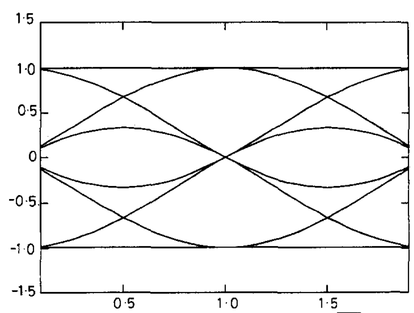


**Fig. 1** *Three-level modulator drive waveform*

A modulator drive waveform similar to that shown in Fig. 1 has been used in tests. This three-level partial response (duobinary) waveform has a reduced bandwidth compared with a normal binary waveform, and the resulting optical signal has a similarly reduced bandwidth. Considering the intensity of the optical signal, the central level results in maximum extinction, the '0' optical level, while the two outer levels result in equal intensities, the '1' optical level. Normally, a peak to peak drive amplitude equal to $\sim 2.V\pi$ would be used to give a signal of maximum optical output. The need for this normally rather large drive amplitude is offset by the relaxed bandwidth requirements of the modulator and drive circuitry.