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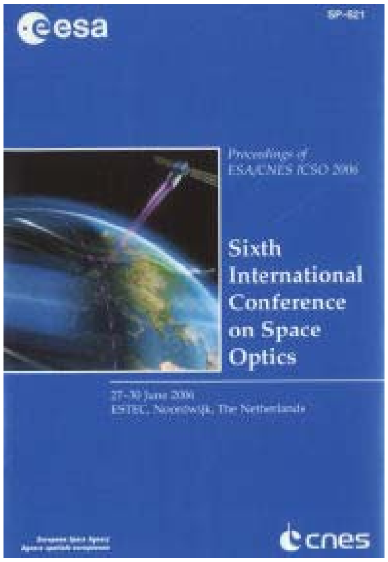

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# *Multimode polymer waveguides for high-speed optical interconnects*

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# MULTIMODE POLYMER WAVEGUIDES FOR HIGH-SPEED OPTICAL INTERCONNECTS

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## ABSTRACT

Polymeric multimode waveguides are of particular interest for optical interconnections in short-reach data links. In some applications, for example in space-borne systems, the use of advanced materials with outstanding performance in extreme environments is required (temperature and radiation). In this paper therefore, we present novel siloxane polymers suitable for these applications. The materials are used to form straight, 90° bent and spiral polymer waveguides by low-cost conventional photolithographic techniques on FR4 substrates. The samples have been tested to investigate their propagation characteristics and demonstrate their potential for high-speed data links. Overall, there is strong evidence that these multimode waveguides can be successfully employed as high-speed short-reach data links. Their excellent thermal properties, their low cost and the simple fabrication process indicate their suitability for a wide range of space applications.

## 1. INTRODUCTION

There is a continuing growth in demand for data communications. In turn this has led to the development of high capacity short-reach interconnections. The capabilities of existing interconnection technology based upon metal wiring architectures and sophisticated electronic techniques are likely to prove inadequate to meet the requirements of the next generation systems due to inherent disadvantages [1]. Optics has been thought to be a promising solution to the bottleneck imposed by conventional technologies as long as it proves able to meet the necessary cost requirements while allowing successful integration in the existing architectures and industrial manufacturing processes [2]. The development of polymer materials, low cost high efficiency laser sources and detectors as well as novel hybrid optoelectronic architectures, are thus of great importance for optics to be feasible and attractive [3]. Multimode integrated waveguides are of great interest as they are likely to meet the expected bandwidth requirements of short reach interconnections and offer a low cost solution due to the reduced alignment tolerances and simple fabrication process.

Materials for use in integrated optical components should be capable of enduring the manufacturing processes of conventional electronic boards. The processes include soldering and lamination that involve long-term exposure to high temperatures and pressures. Polymer materials satisfy these requirements as they exhibit high thermal and chemical stability and possess favourable electrical and mechanical properties such as high resistivity, low dielectric constant, light weight and flexibility. Moreover, they exhibit low manufacturing costs, relatively simple fabrication processes, and can be easily integrated in printed circuit boards (PCBs) [4]. For example, photolithography, hot embossing, reactive ion etching and moulding are some of the fabrication techniques that are being used.

Optical interconnection technology has also focussed on the development of vertical cavity emitting laser (VCSEL) sources. These low cost devices possess excellent optical properties and can be easily integrated onto PCBs [5]. They exhibit a very low threshold current, moderate optical power (few mWs), very high direct modulation bandwidth, wide operating temperature range (-55°C to +125°C) as well as reduced sensitivity to temperature fluctuations [6]. These devices can also be easily packaged in an array configuration due to their unique surface-normal output nature. The configuration of a typical optoelectronic interconnection system using an array of optical waveguides is shown in Fig.1.

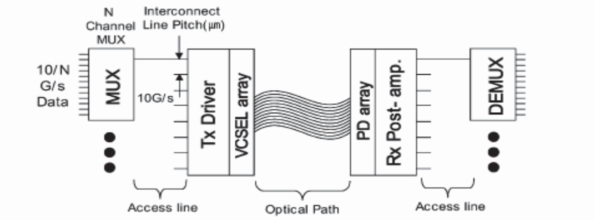

Fig. 1. Optoelectronic interconnection system configuration [7]

This paper presents the fabrication of multimode polymer waveguides and their characterisation studies in order to show their viability for short-reach high-

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speed optical interconnects and suitability for space-borne applications.

## 2. MATERIAL AND FABRICATION

The novel siloxane polymers reported in this work exhibit excellent thermal properties and reliability over a wide range of temperatures as they are capable of withstanding temperatures in excess of 250°C. Therefore, they can be efficiently integrated with conventional PCBs and successfully operate in extreme temperature environments.

The waveguides presented are fabricated by conventional photolithographic techniques. Resins are spun directly onto FR4 substrates and the samples are developed using an ultra-violet (UV) quartz mask and solvent. 50 μm-wide straight waveguides with lengths up to 0.11m, and 1.4m-long spiral waveguides (Fig. 2) with a pitch of 250μm have been fabricated, as well as 90° bent waveguides with a pitch of 1mm and a varying radius of curvature from 1mm to 20mm. All samples are cut using a Disco 321 dicing saw.

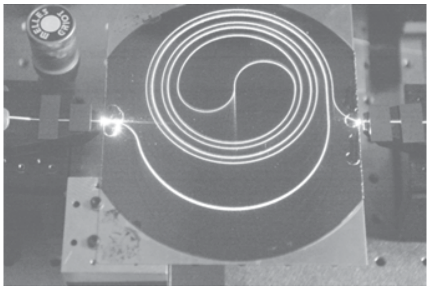


Fig. 2. The 1.4m long spiral waveguide.

## 3. CHARACTERISATION STUDIES

A wide range of measurements have been carried out on the fabricated waveguides so as to determine their propagation characteristics and demonstrate their suitability for high-speed datacommunications. First, the intrinsic attenuation due to material absorption and surface roughness has been measured at the operating wavelengths of 850nm and 1300nm and found to be in the range of 0.03-0.05 dB/cm and 0.36-0.4dB/cm, respectively. Measurements at an 850nm wavelength on samples fabricated on silicon substrates have yielded nearly identical results, indicating that the cladding material sufficiently masks the roughness of the FR4 substrate. Solder reflow studies on waveguides samples fabricated on silicon substrate show a change of the intrinsic attenuation at the 850nm wavelength as a function of the maximum temperature in the process as depicted in Fig. 3. Results indicate that low loss waveguides could be fabricated if a lead-free technology and high-melting-point solders such as AgSnCu, are used in the fabrication process.

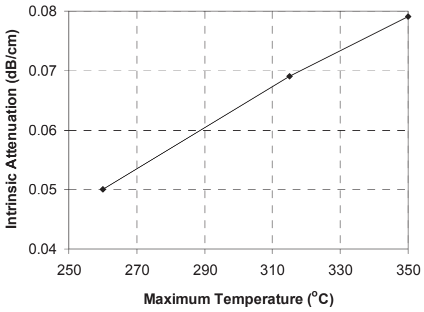


Fig. 3. Intrinsic attenuation at 850nm as a function of maximum temperature of solder reflow process.

Stability of power transmission has been further investigated for temperatures up to 90°C. The transmitted power over a 50μm-wide straight waveguide (length 44mm) has been recorded while horizontally misaligning the input fibre for various temperatures. Results in Fig. 4 indicate that operation at high temperatures do not have a severe impact on transmitted power and misalignment tolerances. Overall, a slight increase of the insertion loss (0.2dB), a slight decrease in misalignment tolerances for the -3dB points (5μm in total) and a slight increase in background scattering noise (3dB) is observed.

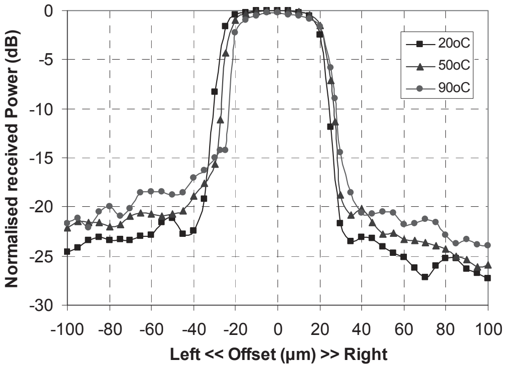


Fig. 4. Normalised received optical power for horizontally misaligned input for different temperatures

Misalignment tolerances for the -3dB points have been measured to be ±25μm and ±10μm at room temperature for the straight and spiral waveguides respectively. The reduced alignment tolerances for the spiral waveguides can be attributed to their spiral shape as higher-order modes are stripped at the bends. Recorded near-field images are in agreement with the above assumption as the light is found to be strongly confined in the centre of the waveguide core even for large offsets of the input fibre.

The 90° bends are used to determine the induced excess power loss for radii up to 20mm.The excess loss is found to saturate for radii larger than 8mm at the value of 0.1dB per mm of radius of curvature (Fig. 5). The low intrinsic attenuation at datacommunication wavelengths suggest that the waveguides can be used for short–reach interconnects, while the low induced excess loss of the 90°-bends show that curved optical paths can also be utilised.

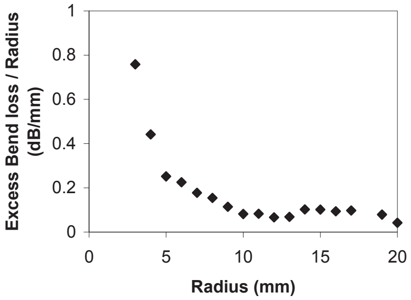


Fig. 5. Excess loss of the 90° bent waveguides per mm of radius of curvature.

A VCSEL source operating at a wavelength of 850nm is used to investigate the performance of the 1.4m long spiral waveguide for high-speed data transmission. A cleaved single-mode fibre couples light into the waveguides and a cleaved 62.5μm multimode fibre (MMF) pigtail is used to collect the output emission and deliver it to a 8GHz photodetector. Index matching gel is used at both ends to maximise coupling efficiency. The frequency response (Fig. 6) of the waveguide is measured with a network analyser and is found to be flat over at least the 7GHz instrumentation limit and remained so, even when the input fibre is misaligned from the position of maximum power transmission.

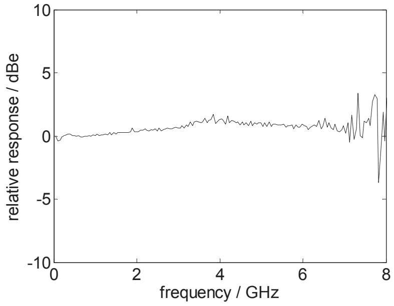
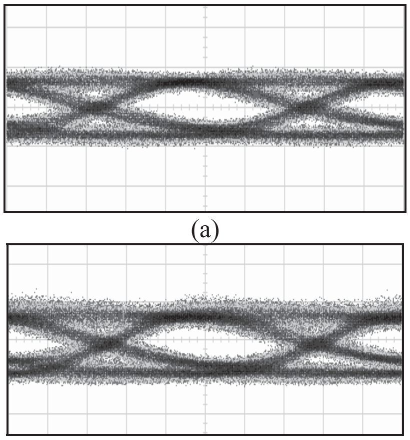


Fig. 6. Frequency response of the 1.4m long spiral waveguide.

High-speed operation has been further confirmed by recording the eye diagrams and carrying out BER measurements. The laser source is directly modulated by a 10Gb/s $2^7$-1 PRBS, so as to mimic the short-length line codes used in datacommunications, while a pair of 10x microscope lenses is used to couple light into the waveguide. The back-to-back link uses coupling of the light from the laser source to the MMF pigtail via the pair of input lenses. The eye diagrams in Fig. 7 indicate that negligible additional noise and pulse dispersion are induced with the insertion of the 1.4m long spiral waveguide, while the bit-error-measurement demonstrates error-free transmission and a power penalty of less than 2dBo.


(a)

(b)

Fig. 7. Recorded eye diagrams at 10Gb/s data rate (time scale: 20ps/div) (a) back-to-back link, (b) at the output of the 1.4m long spiral waveguide.

To further investigate the robustness of the link performance, a single pulse at 10GHz rate has been launched into the waveguide for offsets in the range of ±15μm, while the full width at half maximum of the received pulse is recorded. The pulse width remains relatively stable for offsets up to 10μm, indicating that the input misalignment does not increase inter symbol interference (Fig. 8).

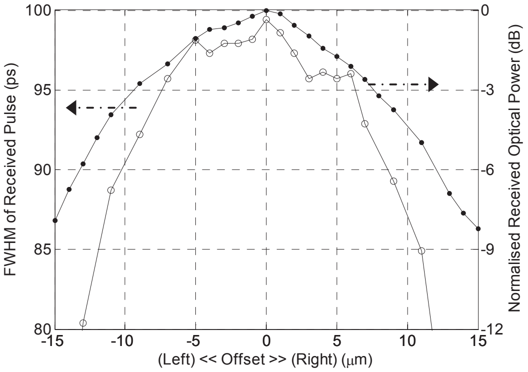


Fig. 8. Normalised received optical power and full width at half maximum of the received pulse for offset input launch in horizontal axis.

Induced crosstalk at adjacent waveguides for both the straight and 90°-bent samples has been measured while varying the position of the input fibre (Fig. 9). The maximum recorded value for the straight waveguides is -32dB, obtained when the input fibre is near the edges of the adjacent waveguide, while it decreases to -45dB for central launch. Moreover, it is confirmed that crosstalk values do not change significantly for various input launch conditions (vertical misalignment or tilted launch up to a 5° angle). For the 90°-bent waveguides, the maximum crosstalk drops to -60dB for radii larger than 2mm (Fig. 10). This impressive result is also partly due to the increased separation distance (1mm) between adjacent waveguides in comparison with the 250μm pitch of the straight samples. The low crosstalk values for both straight and curved waveguides suggest that dense optical interconnects are feasible, while results in Fig. 10 indicate that a reduced pitch spacing (100μm) can be achieved with no significant crosstalk degradation.

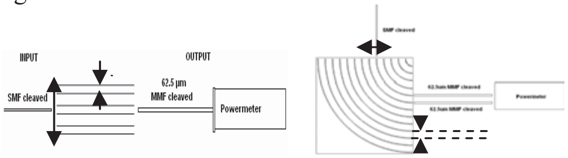
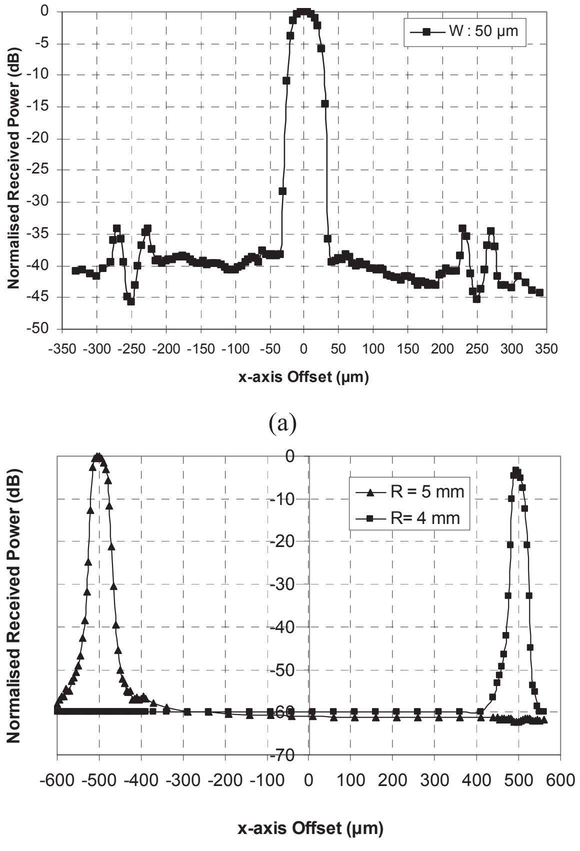


Fig. 9. Crosstalk measurement setup.



(a)

(b)

Fig. 10. Crosstalk results for (a) straight waveguides with a 250μm pitch (b) 90° bent waveguides (radii: 4.5mm) with a 1mm pitch

## 4. CONCLUSION

The low power attenuation at datacommunication wavelengths, the flat frequency response over a wide range of frequencies and the low crosstalk values demonstrate the suitability of novel siloxane polymer multimode waveguides for short-reach, high-speed data links. The recorded eye diagrams and the BER measurement show efficient 10Gb/s data transmission over a 1.4m long spiral waveguide. The excellent performance is maintained over a wide range of input launch conditions and temperature environments. The thermal properties of the polymer material, the low cost and simple fabrication process enabling the integration of the waveguides onto conventional PCBs, further indicate their potential use in space-borne applications.

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