Cost-Effective Polymer Multimode Directional Couplers for High-Speed On-Board Optical Interconnects

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Abstract: *Cost-effective polymer multimode directional couplers suitable for high-speed on-board optical interconnects are presented. Power splitting ratios from 30 to 75% are achieved, symmetric behaviour is obtained for both input arms and robust performance in terms of input misalignment is demonstrated. No special fabrication steps are required for patterning the devices.*

Introduction

Polymer multimode waveguides have become increasingly of interest for use in short reach optical interconnects in recent years as they offer a promising solution to the bottleneck imposed by conventional electronic circuitry [1,2]. Their main advantage consists of low-cost and simple fabrication processing compatible with the existing manufacturing process of electronic printed circuit boards (PCBs). The siloxane materials reported in this work exhibit excellent thermal and mechanical properties and are able to withstand the in excess of 250^{o}C temperatures that are required for solder reflow processes [3]. Moreover, owing to their reduced alignment tolerances, multimode waveguides allow for reduced cost connectorisation and packaging. Yet further cost advantages and increased functionality could be achieved by directly forming passive components in the polymer guides.

Interconnection architectures comprising an optical bus and various optical stations or cards require the use of passive add/drop devices (Fig. 1). The majority of multimode devices, however, offer only a 3dB power splitting ratio as a result of mode mixing and power redistribution between the large numbers of modes inside the guides [4-5]. Being able to control the power splitting ratio is therefore an important attribute for any passive component to be employed in such add/drop applications. In this paper we report the fabrication and characterisation of directional multimode coupler devices patterned by conventional photolithographic techniques on FR4 substrates which are suitable for use in on-board optical interconnects. Despite the multimode nature of the guides and the low potential cost of the devices, good performance is achieved even in the presence of significant input misalignments.

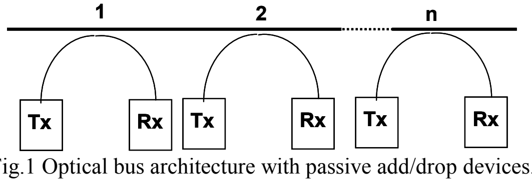


Fig.1 Optical bus architecture with passive add/drop devices.

Device design and fabrication

The devices are fabricated on a FR4 substrate by conventional photolithographic techniques from silicone OE4140 (core) and OE4141 (cladding) polymer materials. The waveguide cross section is 50×50 μm^2 so as to match standard 50/125 μm multimode fibre systems (MMF) while the waveguide separation is chosen to be 250 μm to comply with conventional fibre ribbon, VCSEL and photodiode array spacing. The intrinsic waveguide loss is measured to be 0.03-0.05 dB/cm at an 850 nm wavelength.

The couplers consist of a pair of 6 mm long raised-cosine S-bends and a middle interaction section whose length L_{mid} is varied from 0 to 4.5 mm. The total length of the device is 20 mm. Fig. 2a shows a schematic of the coupler design. It should be noted that the two coupler arms are in contact so that no separation gap exists in the interaction section. Due to the large index step between the core and cladding material (Δn~0.02), the separation distance that is required to ensure efficient power coupling between the two guides, is in the order of a few microns (~5 μm) – a value much smaller than the height of the core polymer layer (H=50 μm). Standard low-cost photolithographic techniques fail to efficiently produce features of such an aspect ratio as vertical sidewall deformation occurs (Fig. 2b-2c). By merging the two arms together at the interaction region, no extra fabrication steps (i.e. etching process) are required in order to create the necessary narrow gap, allowing thus an easier patterning and simplified fabrication. Nevertheless, the convergence of the arms will eventually create similar defects near the junction points (points A-B in Fig. 2a) at both the input and output sides of the device, inducing as a result additional excess loss.

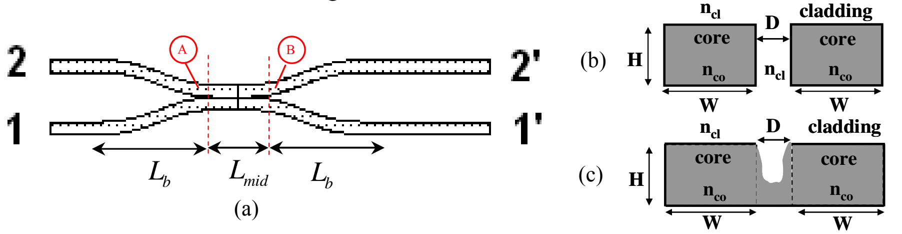


Fig.2. Schematic of (a) a polymer coupler and (b-c) illustration of the cross section of fabricated parallel waveguides in the case of (b) a large ($D / H >> 0.5$) and (c) a small ($D / H < 0.5$) feature aspect ratio.

The multimode polymer coupler can be treated as a multimode interference (MMI) device [6] which, in this case, has multimoded input and output arms. The power coupled to each one of the guided modes inside the interaction region depends on the power distribution and the relative phases of the modes of each one of the input arms (point A), while the power coupled to each one of the output arms depends on the interference between the modes of the interaction region at the output arms-interaction region interface (point B). Therefore the operation of the device and, more specifically the power splitting ratio between the output arms, depends strongly on the length of the interaction region and the mode distribution inside the input arms. Furthermore, the input and output S-bend regions affect the device behaviour as their converging input and diverging output waveguides result in additional mode coupling between the arms of device. Our goal is to investigate the performance of the device in the case of an overfilled launch into each arm of the device and evaluate the robustness of the splitting power ratio in the presence of input misalignments (which are expect to be likely in low-cost integrated optical systems). Therefore, multimode fibre (MMF) launches are employed in order to create a mode power distribution at the input arms as uniform as possible while representing an input configuration scenario that could be met in real-world applications (e.g. a fibre ribbon – polymer optical board interface).

Characterisation studies

A standard 850 nm multimode VCSEL source is used as a transmitter while a standard cleaved 50/125 µm MMF patchcord is used to couple light into each of the device's input arms. A 62.5/125 µm butt- coupled MMF is used to collect the light at each output arm and deliver it to an optical power meter. Index matching gel is used at both waveguide ends to maximise coupling efficiency. The excess loss of the devices is 0.8 dB for a 50/125 µm MMF input and can be attributed to the bending loss induced by the input and output S-bends and the acute point at the convergence region of the input and output arms (points A and B).

In fig. 3 the variation of the splitting ratio of output power (fraction of output power coupled into the antisymmetric port: 1→2' and 2→1') as a function of the length of the interaction section L_{mid} of the device is shown. A symmetric response is obtained for both input arms while the percentage power coupling varies from 30 to 75% depending on the interaction length L_{mid}. Moreover, similar behaviour is observed for both multimode fibre input configurations. The same black fit line is shown in both plots in order to simplify the comparison. The observation indicates the robustness of the operation of the multimode couplers on launch conditions as long as those are kept close to being overfilled. Owing to the multimode nature of the devices, complete power coupling into the antisymmetric port cannot be achieved. The minimum coupled power percentage obtained is approximately 30% for a nominal interaction section length of L_{mid} =2 mm. Larger interaction lengths lead gradually to a smaller power coupling fraction variation due to the mode mixing occurring inside the interaction region.

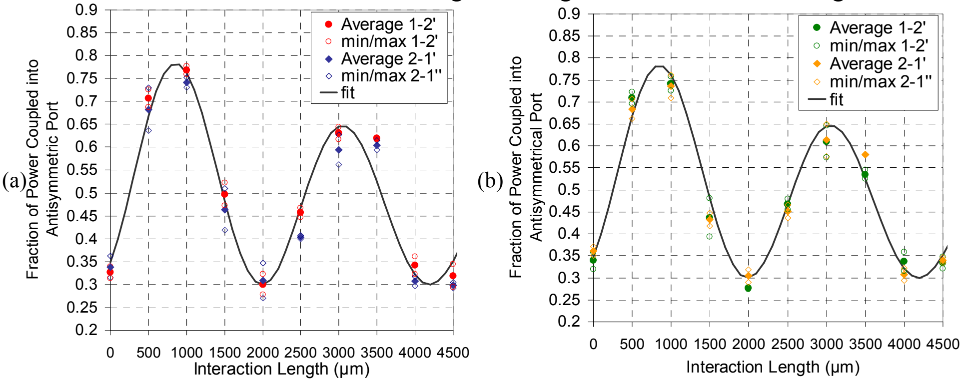
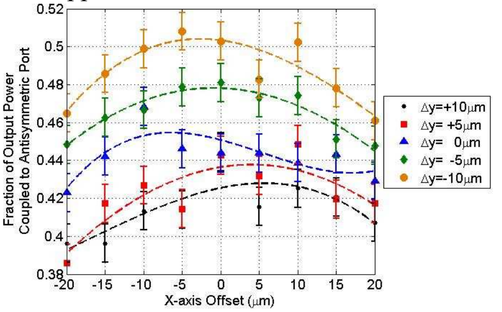


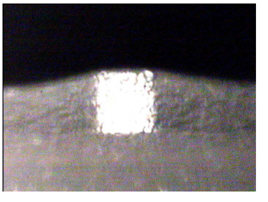
Fig. 3. Fraction of output power received at the antisymmetric port as a function of interaction length L_{mid} for a (a) 50 µm and a (b) 62.5 µm MMF input.

For each device and for each input port, the worst-case behaviour scenario is implemented by adjusting the position of the input fibre with a 3D translation stage so as to maximise the power received in one of the output arms of the device. The input fibre is kept constant while recording the power received at the other output. The maximum variation of the splitting ratio for every device can be obtained providing thus an indication of the robustness of the device performance. The non-filled points in Fig. 3 represent the minimum and maximum power fractions achieved by this technique. The average variation for all devices under investigation obtained is ±2.5% while the maximum value recorded is approximately ±5% for the device #4 (4^{th} device in Fig. 2) with an interaction section length of L_{mid}=1.5 mm.

To further investigate the effect of input misalignment to the operation of the couplers, the performance of the device #4 exhibiting the greatest power splitting ratio variation is studied in more detail. The received power at the device's two output arms is recorded while offsetting the input MMF both in the horizontal and vertical direction (Fig. 4a). It can be noticed that for horizontal misalignment a symmetric behaviour is obtained while the maximum power splitting variation is smaller than 5% (±2.5%) for an input offset of ±10 μm for all vertical input positions. Vertical misalignment however leads to an asymmetric behaviour and slightly greater variation. Offsetting the fibre towards the substrate leads to a small change in the splitting ratio (< 3%) whereas an upward input fibre movement has a greater effect. This can be attributed to the asymmetry of the cross section of fabricated waveguides in the vertical dimension (Fig. 4b). Increasing the thickness of the top cladding layer is expected to overcome this issue. Overall, the observed power splitting variation due to input misalignment of this "worst-case" coupler is relatively small, demonstrating thus the potential of the use of the devices in real-world applications.

(a)





(b)

Fig. 4. (a) Fraction of output power received at the antisymmetric port as a function of horizontal input offset for different input vertical positions for device #4 and (b) photograph of one of the output waveguide facets of the device when illuminated with the VCSEL source.

Conclusion

Low cost polymer multimode directional couplers fabricated on FR4 substrate exhibiting a power splitting ratio between 30 and 75% are presented. Despite being highly multimoded structures, symmetric behaviour for both input arms and robust performance are achieved, even in the presence of input misalignment in the order of 10 microns in both horizontal and vertical directions. The devices are suitable candidates for use in high-speed on-board optical interconnection schemes.

References

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