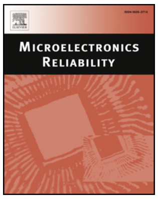
Microelectronics Reliability 84 (2018) 121–126

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel



Optical coupling with flexible polymer waveguides for chip-to-chip interconnects in electronic systems

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A R T I C L E I N F O

Keywords:
Optical waveguides
Coupling optics
Bus coupler
Out-of-plane optics
Flexible substrates
Electro-optical integration
Optical characterization
Optical chip-to-chip interconnects

A B S T R A C T

This contribution discusses technology development for the realization of chip-to-chip interconnection based on flexible optical waveguides. Two approaches for optical coupling between waveguides and active devices are presented. Both approaches built on the planar polymeric optical multimode waveguides integrated on flexible substrates (PEN-foil). This waveguides structured using UV-photolithography and Ormocere-materials feature low optical attenuation below 0.05 dB/cm. The first approach for coupling between optical waveguides uses a bidirectional interruption-free waveguide coupler. The principle bases on directional core-core-coupling and allows for adjustable coupling ratio by tuning the overlap area. In addition, an asymmetric coupling behavior depending on the coupling direction due to a bending of one of the coupling waveguides is achieved. This coupling method shows supremacy for optical bus systems where tunable, asymmetric coupling ratios are desired. The second optical coupling approach for waveguide-to-chip coupling bases on out-of-plane optics. Direct integration of 45° micro-mirrors into polymer waveguides using dicing process is investigated. Two approaches for optoelectronic (OE) subassembly with flexible optical waveguides are considered one with flip-chip bonded and one with embedded OE-devices. Using optical characterization the influence of fabrication parameters on the optical performance of diced mirrors with insertion power loss measurement is derived and presented.

1. Introduction

The growing bandwidth demand in the future inter-chip interconnects calls for development of competitive solutions that combine high performance and low packaging complexity at acceptable costs. A promising approach to increase performance in the future electronic systems are integrated optical interconnections. The evolution of high-performance computing (HPC) systems and data servers is in last decades the main driver for introduction of optics in electronic systems [1]. Since 2005 optical fibers have been introduced for fast rack-to-rack local connections in HPC-systems [2]. Recently, additional requirements as energy efficiency and bandwidth density evolved, which prove the supremacy of optical solutions in comparison to electrical copper-based interconnects for short-reach links on board- and backplane level. But also new application scenarios such as Internet of Things (IoT) and Industry 4.0 can profit from advantages of optical short-range connections (low weight, electro-magnetic immunity, low power consumption) and are discussed as alternative for off-chip connectivity [3]. Optical integrated planar waveguides are very promising approach to realize short reach interconnects as electro-optical PCB or large area optical foils in order to avoid elaborate and expensive handling of fibers. Glass [4] and polymer [5,6] are the most preferred waveguide materials for cost-efficient electro-optical integration in rigid substrates. In this work, the integration of planar polymeric multimode waveguides into flexible substrates is investigated. This enables 3D integration with open form-factor and cost-efficient manufacturing of electro-optical systems.

In order to realize an inter-chip connection the optical interface between integrated waveguides and optoelectronic (OE) devices needs to be defined. Efficient (low-loss) and robust schemes for optical in- and out-coupling from integrated waveguides at different interconnection levels is a prerequisite. Two coupling interfaces – direct coupling from OE-chip to waveguide and coupling between waveguides – are considered in order to enable full, end-to-end (from transmitter to receiver OE-chip) optical interconnection through different interconnect levels, as shown in Fig. 1. For the links with vertical emitting/detecting OE-devices (vertical-cavity surface-emitting lasers (VCSELs) or Si-photonic devices with Bragg couplers), considered in this work, the coupling into planar waveguides requires light redirection. This is realized by using micro-mirrors integrated into the waveguide [7–9] or by incorporation

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https://doi.org/10.1016/j.microrel.2018.03.020
Received 12 January 2018; Accepted 17 March 2018
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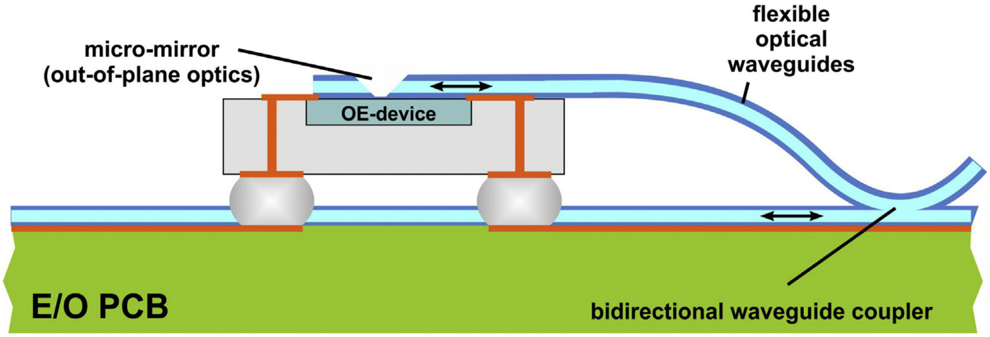


Fig. 1. Concept of electro-optical system integration.

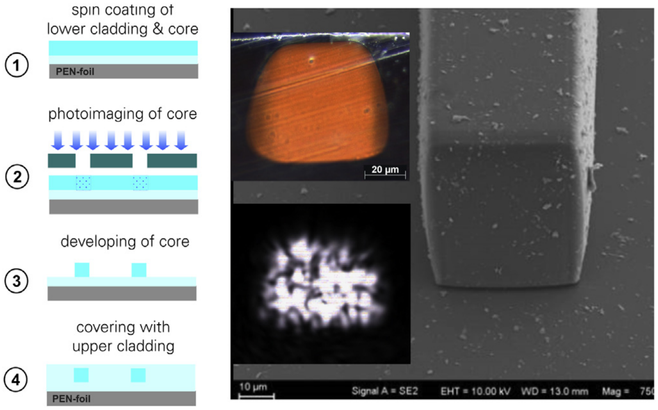
of additional micro-optical element with redirection function [10–12]. Because of low complexity of the first approach, a direct integration of 45° micro-mirrors into polymer waveguides is investigated in this work (see section IV). The second interface connects waveguides between different interconnect levels is typically realized by bulky butt-coupled connectors (e.g. MT-ferrule based connection), which additionally need the interruption of connecting waveguides. In contrast to that, our approach for coupling between optical waveguides considers a bidirectional interruption-free waveguide coupler, which is based on directional core-core-coupling principle and allows for adjustable coupling ratio by tuning the overlap area (see section III). In addition, an asymmetric coupling behavior depending on the coupling direction due to a bending of one of the coupling waveguides is achieved.

2. Flexible optical waveguides

In this work, multimode waveguides are discussed since relative large core dimensions (30–50 μm) lead to relaxed alignment tolerances, which are essential for incorporation of a passive alignment scheme. The planar strip waveguides were fabricated using Ormocer® hybrid organic-inorganic material, produced by sol-gel synthesis. For realization of strip waveguides with fully cladded waveguide's core, commercially available material combination – Ormoclad and Ormocore – has been used. With this material combination waveguides have an index contrast of $\Delta = 0.014$ ($n_{core} = 1.550$ and $n_{cladding} = 1.528$ at $\lambda = 850$ nm), which yields to a numerical aperture of NA = 0.26. Mixing of Ormoclad and Ormocore materials enables changing of the index contrast and thus the numerical aperture NA, which influence intermodal dispersion of the discussed planar multimode waveguides and thus determines max. Waveguide's bandwidth (this influence has been studied in [13,14]). As mentioned in the introduction in this work flexible substrate (heat-stabilized polyethylene-naphthalate PEN foil) has been incorporated. Using flexible optical waveguides coupling between two points on non-planar (3D-formed) surface can be realized. Prior to deposition and structuring of the waveguides, the PEN foil has to be temporarily bonded to a rigid carrier Si-wafer. The selected PEN-foils (Teonex® Q65H) with 50 μm thickness is on one side pretreated, which enables direct (without using additional adhesive) lamination on the carrier wafer.

The used PEN-foils feature low surface roughness ($R_a = 0.7$ nm) and high transparency enabling the use of this material as transparent substrate for optical signal transmission without via fabrication.

The Ormocer®-material is structured using UV-photolithography (negative type). In this work mask-based UV-photolithography was applied for the structuring of core and cladding material. In Fig. 2 (a) processing steps for UV-structuring of the strip waveguides are depicted. The cladding and core layers are deposited on a 6″ carrier wafer with flexible substrate using spin coating. In order to provide good material wetting and adhesion prior to deposition the wet-cleaning and O2-plasma surface treatment has been performed. The waveguide core was structured using proximity mask exposure followed by a post exposure bake and an immersion developing step. In Fig. 2(b) a SEM image of a waveguide core with well-defined core cross section shape and good height-to-width aspect ratio is shown. In order to achieve strip waveguides with fully cladded waveguide's core in the last fabrication step the covering with the upper cladding polymer and hard baking of the layer sandwich were performed. In the top inset of Fig. 2(b) the core cross-section of the polymer waveguide core with surrounded cladding after end-face preparation is shown. For evaluation of the optical performance of fabricated waveguides, optical attenuation using cut-back method have been measured. Low optical attenuation coefficients below 0.05 dB/cm are achieved, which proves the applicability of the fabricated waveguides for low-loss on-board optical data transmission [13]. In order to prove the usability of the polymeric waveguides for high-speed optical data transmission, transmission tests for data rates up to 25 Gbit/s at a wavelength of 850 nm have been performed - error free transmission (BER < 10^{-12}) up to 30 Gbit/s for 9 cm-long planar waveguides are achieved [15]. The near-field analysis of fabricated waveguides proves the multi-modal behavior of the waveguides. Full mode-filling of core cross-section are observed (bottom inset of Fig. 2(b)).



(a) (b)

Fig. 2. Fabrication of flexible optical waveguides: process steps for UV-structuring of strip waveguides based on Ormocer® material (left), SEM image of a waveguide core manufactured using proximity mask exposure; inset pictures show core cross-section after end-face preparation (top) and near-field mode distribution in waveguide's core (bottom).

3. Bidirectional interruption-free waveguide coupler

3.1. Concept and simulations

To use waveguides in optical short-range connections, e.g. for IoT and Industry 4.0 solutions, the integration of interruption-free

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