Highly reliable polymer waveguide platform for multi-port photonic chip-packaging

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Abstract—Photonic integrated circuits (PICs) have become an integral part in many high-performance sensing and leading-edge high-speed communication applications. At present, unlocking the full potential of PICs is still impeded by the limitations of traditional optical assembly schemes. Using butt- or grating coupling only enables to access a very limited number of optical interfaces and has large space requirements dictated by the comparably large optical fibers. By addressing these challenges, planar polymer waveguides, integrated into compact electro-optical-circuit-boards (EOCBs), present a viable option for next-generation chip-packaging. Their polarization maintaining properties and high-power operation render them a suitable platform for many telecom and sensing applications.

Keywords — electro-optical-circuit-board, packaging, polymer waveguides, optical coupling, photonic integrated circits

I. INTRODUCTION

The increasing demand for ever increasing processing performance and high-data throughput networks is driving the developments of PIC-based transceivers and routing technologies [1]. Packaging is an important part in the development of PIC devices and applications. In order to overcome the challenges associated with packaging, a high-performance and robust photonic board concept is presented. The key elements of these EOCBs are singlemode polymer waveguide fan outs with multiple parallel channels (>10) that allow PICs to be coupled efficiently to several in- and outputs at the same time. This drastically improves the accessibility to the on-chip capabilities of PICs and hence extends their application range. In addition, functional structures such as splitters and combiners can be incorporated directly into the photonic boards. Most importantly for advanced sensing or telecommunication applications, these elements have been found to be highly insensitive to the input polarization and exhibit polarization-maintaining properties. Moreover, the single mode polymer waveguides, as well as passive elements thereof, are fully operational at high optical powers of several tens of milliwatts in the C-band

The paper further presents recent results of the polymer waveguide technology and discusses application examples. Within the H2020 ICT-STREAMS project, an optical chip-to-chip communication scheme based on adiabatically-coupled polymer waveguides was shown [2]. The photonic demonstrator board supports wavelength division multiplexed (WDM) signals of 400 Gbit/s per channel, with an envisioned total on-board throughput of 12.8 Tbit/s on a 16 node server board [3].

As a further example, the use of the EOCB platform within the EC-funded H2020 ICT-QAMeleon project is presented [4]. Here, a photonic board is used as a host substrate for a hybrid Indium Phosphide – Liquid Crystal on Silicon (InP-LCoS) assembly, including micro-optical elements to couple light into free space using polymer waveguide front-ends.

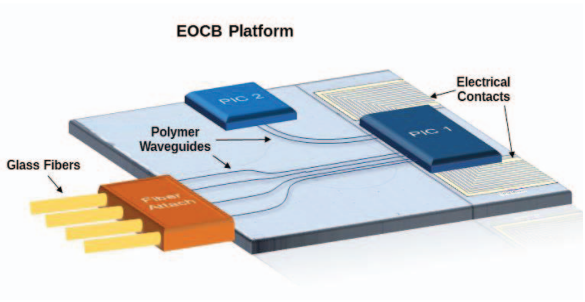

Fig. 1 . Schematic overview of a PIC packaging solution using an EOCB platform. Polymer waveguides can be used to route light between several PICs or to connect a PIC to glass fibers.

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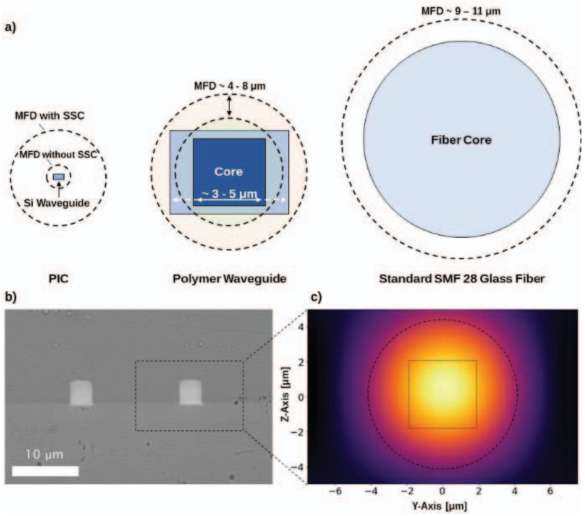

Fig. 2. Optical properties and specifications of polymer waveguides. (a) Comparison of the core dimensions and mode field diameters of a Si waveguide, a polymer waveguide and a glass fiber, respectively. (b) Cross-sectional micrograph of a polymer waveguide core and (c) its corresponding mode field distribution.

II. EOCB CONCEPT

Traditional chip-packaging routines such as direct fiber to PIC attachment rely on domain-specific engineering of the electrical and the optical interface separately. This typically implies the use of several individual parts – e.g. single fibers, fiber array blocks and electrical PCB parts – and thus involving many assembly steps for each piece. While this is reasonable for applications using a single PIC with only few optical ports, this approach is not practical anymore in systems comprised of multiple PIC-based computing nodes or other advanced hybrid architectures. In these more complex applications, it is highly advantageous to combine electrical, optical and eventually mechanical interfaces in a single EOCB platform, in order to reduce packaging efforts (Fig. 1). This, of course, also has strong implications on the specifications and requirements for the manufacturing of such a board. While the details of the fabrication and characterization of the electrical part of the EOCB platform have been discussed before [5][6], this work deals with the optical parts.

III. SINGLEMODE POLYMER WAVEGUIDE TECHNOLOGY

A. *Optical Characteristics*

The optical interface of the presented EOCB platform relies on single mode planar polymer waveguide technology. These waveguides are comprised of a patterned core with an approximately rectangular cross-section, embedded in a cladding material with a lower refractive index. Typical dimensions of the core width and height are around 3.5 µm. The dimensions of the waveguide core, as well as the refractive index contrast between core and cladding determine the optical properties such as the propagation loss and the mode field diameter. The latter is a crucial parameter in the packaging of PICs. Standard PIC platforms (SiPh, InP etc.) are based on high index contrast light guiding. While this allows very dense and sub-micron sized optical structures and waveguides, it also results in accordingly small mode field diameters (MFD) of less than 1 µm (bare Si waveguide) up to 4 µm (using spot-size converters). On the other hand, standard optical fibers exhibit larger MFDs between 9.2 µm and 10.4 µm at telecom wavelengths of 1310 nm and 1550 nm, respectively. This mismatch is one of the biggest challenges for efficient optical coupling to PICs.

In contrast, the optical properties of polymer waveguides not only lie in the middle between those of PICs and optical glass fibers, but as a further feature of this technology, they can be tuned (within a certain range) by a proper choice of core dimension and refractive index contrast, as illustrated in Fig. 2. Therefore, this polymer waveguide-based approach can not only serve as a geometrical fan-out from the narrow pitch on a PIC to larger ones like on fiber-arrays, but also act as an efficient optical link, matching both mode field diameters.

B. *Polarization*

One optical parameter in single mode technology that is of increasing importance in photonic circuits is the polarization. The polarization state of a light-signal can be used as an information channel in fiber sensing systems as well as in advanced channel coding techniques such as polarization-division multiplexing as add-on in WDM systems. In all of these applications it is crucial that the signal does not get distorted, i.e. the polarization state remains unchanged between the source and the receiver. Thus, any optical component along the transmission line, including the optical packaging system, needs to fulfill certain requirements with respect to polarization.

In the case of the presented planar waveguides, their geometry and symmetric shape supports both the fundamental horizontal (TE) and vertical (TM) polarized mode (Fig. 3a and Fig. 3b). Hence it is possible to couple-in light from a source with different, well-defined linear polarization states using a PM fiber, as visualized in Fig. 3c. The transmitted light can be measured using a multimode fiber at the output, connected to a powermeter. Rotating the input PM fiber along its optical axis will result in different input polarizations. Comparing the change in transmission at different input polarizations – TE, TM and diagonally polarization light - reveals a very small variation in the insertion loss (coupling-loss and propagation-loss). The corresponding polarization dependent loss (PDL) at a wavelength of $\lambda = 1550$ nm is smaller than 0.2 dB (Fig. 3d).

Apart from the polarization-independent propagation losses, further measurements on the state of the output polarization. i.e. the ability to maintain the polarization state during the waveguide propagation, were performed. For this purpose, a polarizer was inserted between the waveguide-end and the powermeter. This allows to analyze the polarization state of the waveguide output, while setting the input polarization to either horizontal or vertical, respectively. The polar plots in Fig. 3e and Fig. 3f display the relative intensity as a function of the polarizer

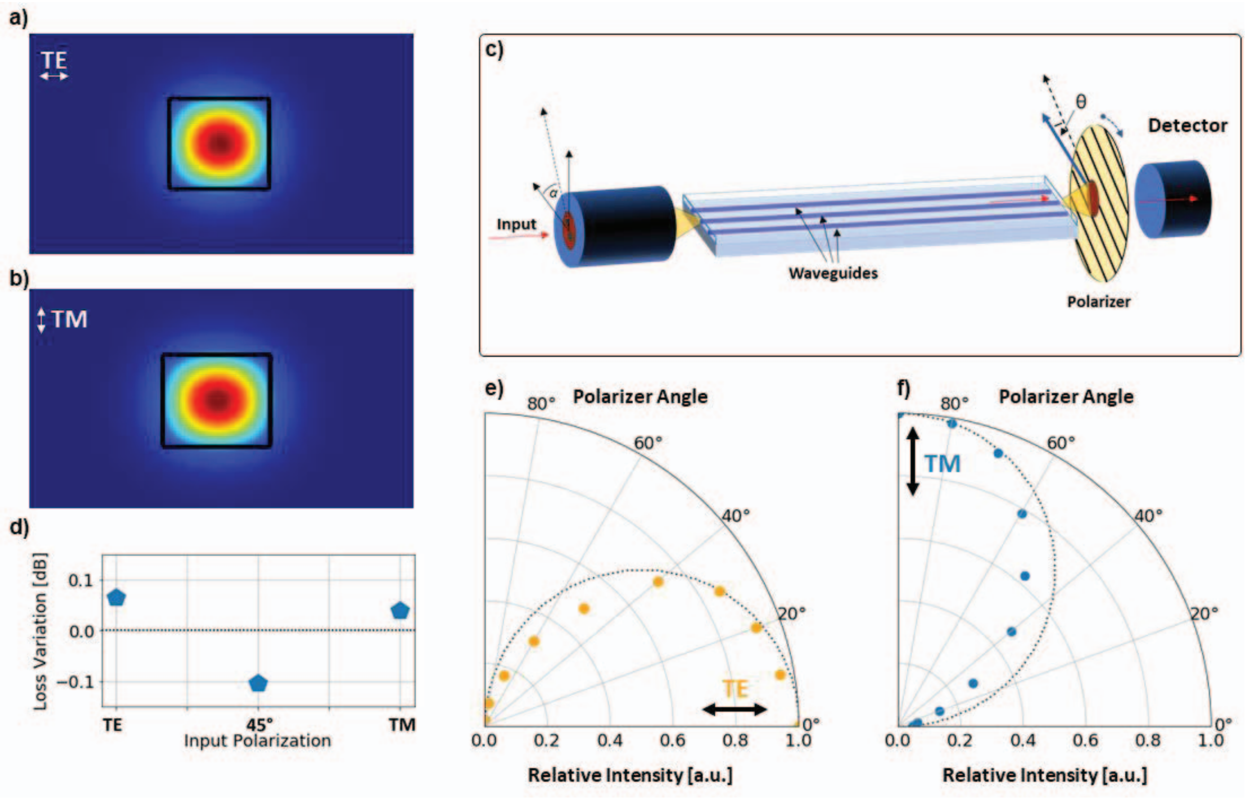

Fig. 3. Measurement of the polarization dependent characteristics of the presented single mode polymer waveguides. a) and b) The quasi-rectangular core supports both the fundamental TE and TM mode, respectively. c) Schematic of the measurement setup. d) Transmission-measurements at different input polarizations indicate a small dependence of the insertion loss on the input polarization. e) and f) The analysis of the output polarization at TE and TM input light, respectively, confirms the polarization maintaining properties of the presented waveguides.

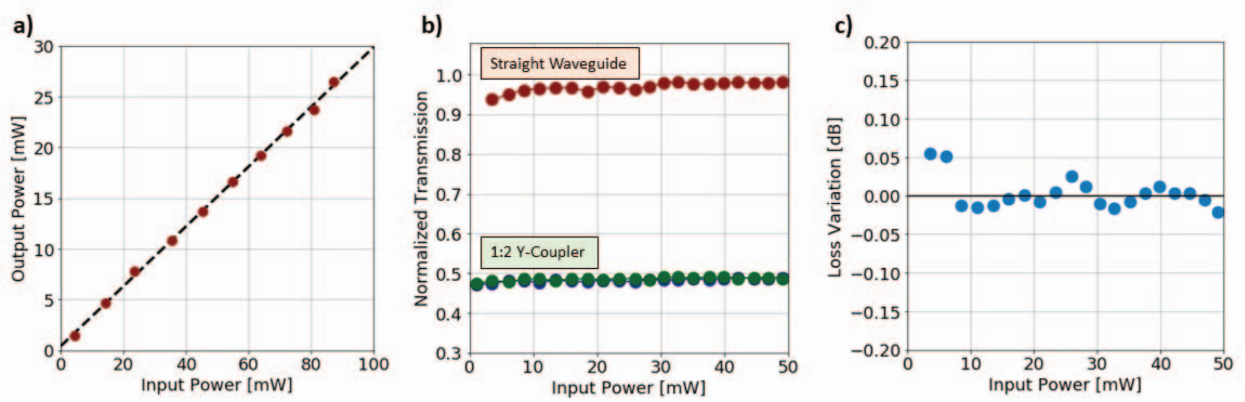

Fig. 4. High-power characterization of the planar single mode technology at a wavelength of 1550 nm. a) Output power of straight waveguides as a function of input power. No damage or degradation at optical powers of up to 90 mW (limit of laser source) was observed. b) Normalized transmission as a function of input power for straight waveguide and a 1:2 Y-Splitter. c) The variation of the loss of a straight waveguide lies between +/- 0.1 dB, independent of the input power.

angle for a fixed input polarization. In both cases, TE and TM input, the characteristics of the measured angular intensity dependence matches that of a perfectly linear polarization. This confirms that the polarization of the input is not only preserved upon coupling into the facet, but also maintained during the propagation through the waveguide. Thus, the measured output polarization remains unchanged with respect to the input polarization.

C. *High-Power Operation*

As a result of the expanding range of possible applications for PICs, their various operating conditions and requirements are growing correspondingly. Many sensing applications, for example, rely on high optical powers to increase the signal-to-noise ratio. It is of fundamental importance that the packaging platform is robust against high optical powers. Therefore, the characteristics of the output power as a function of the input power were measured on relevant structures of the presented platform. Fig. 4 shows the results from transmission measurements using a fiber-coupled single mode laser source operating at 1550 nm, which was directly butt-coupled to the polymer waveguides. Fig. 4a displays the output power, recorded using a multimode fiber at the waveguide end and a power meter. A clear linear trend between input and output power is apparent, i.e. the insertion and propagation loss remain constant. This can also be seen in Fig. 4b and Fig. 4c, where the normalized loss of a straight waveguide and a 1:2 Y-Coupler (splitting one input into two 50% output beams) is shown. It is noteworthy that no damage or degradation was observed up until 90 mW of optical power , which was the limit of the available laser source. Despite the small dimensions of the core cross-section (approximately 3.5 µm x 3.5 µm), both the input facet itself and the waveguides along the propagation direction stay intact at these optical powers. These results indicate an even higher power threshold and extend the suitability of this platform for high-power applications.

D. *Optical Interface to PIC*

While PIC technologies are getting more and more mature, including the developments of advanced on-chip functionalities, efficient optical coupling using traditional approaches (e.g. single fiber to chip connections) are far from being optimal. Especially multi-port chips suffer from the lack of suitable packaging concepts with high integration density. Ideally, an optical coupling interface is able to provide high-efficiency transmission of optical signals with low wavelength dependence (for applications involving WDM or on-chip spectrometers). Moreover, as the assembly process itself is an integral part of any PIC-packaging concept, relaxed alignment tolerances is an important parameter too.

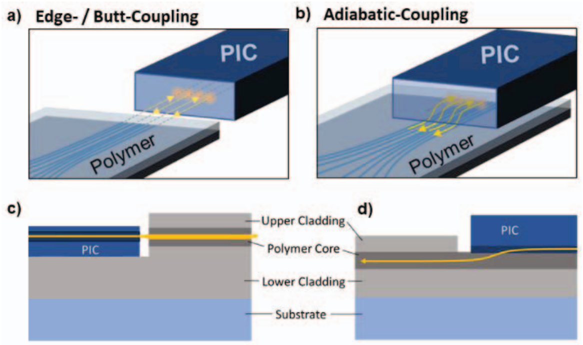

Fig. 5. Schematic concepts of optical coupling schemes used in the EOCB: a) and c) butt-coupling, b) and d) adiabatic coupling interface.

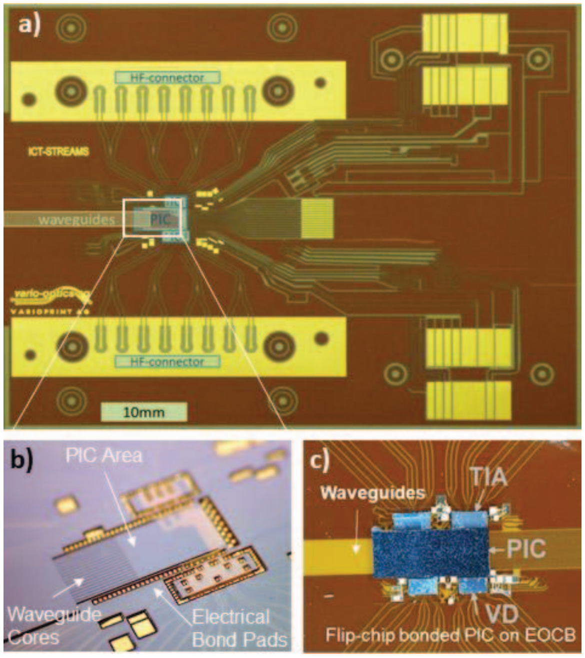

Fig. 6. a) Fully assembled and wire-bonded EOCB Demonstrator (8ch TRx) within the ICT-STREAMS project. b) Zoom-in to the coupling region with bond pads and exposed waveguide cores. c) fully assembled, flip-chip bonded device. Figures adapted from [5].

The most common types of optical coupling solutions, which have evolved within recent years, are a) edge/butt coupling, b) adiabatic/evanescent coupling and c) coupling via gratings [7]. Each of those approaches has its advantages and drawbacks. While interfacing a chip via grating couplers (GCs) provides good alignment tolerances, these structures require a wavelength-specific design, and thus only have a small operating spectral bandwidth with reasonable insertion loss. Typically, such GC-based approaches rely on the precise fabrication of on-chip structures and further imply the use of out-of-plane assembly methods.

On the other hand, both butt- and adiabatic coupling can be realized in an in-plane assembly, as shown in Fig. 5, rendering them suitable schemes for the planar waveguide technology. Adiabatic coupling allows the efficient transfer of the guided mode into the polymer waveguide core, and exhibits relaxed assembly tolerances, given by the size of the core [8]. In a butt-coupling scheme, the alignment is more critical, but it results in a low-loss interface. The presented polymer platform is capable to provide an interface for both of these coupling schemes, the details of which are discussed in the following section.

IV. CHIP-PACKAGING EXAMPLES

Chip on-board direct attachment is a promising route for compact transceiver assemblies. This concept is gaining importance as more and more functionalities are being deployed within PICs, such as AWGRs (arrayed waveguide grating routers) and WSSs (wavelength selective switches). The

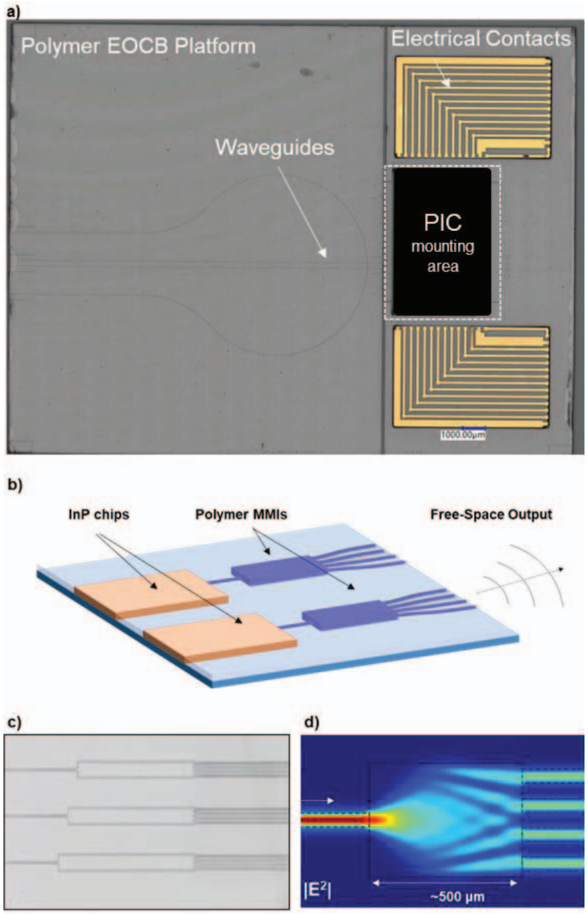

Fig. 7. EOCB used within the ICT-QAMeleon project. a) top-view microscopic image of the host substrate for a InP chip, containing polymer waveguides. b) Schematic of the proposed MMIs for being used as WFEs to launch and receive a beam from free space. c) and d) microscopic picture and simulation of a 1:4 MMI device.

following examples showcase the use of the presented EOCB platform within two European research and innovation projects.

A. *ICT-STREAMS*

ICT-STREAMS is a European research and innovation project focusing on the development of high-data throughput communication between multiple computing nodes based on a silicon photonic platform using any-to-any optical connections [2]. Within the project, a multi-socket EOCB based on the presented polymer platform was developed. The final EOCB, as shown in Fig. 6, consists of an RF electrical interface with small metal pads (125 µm pitch) and a (transparent) polymer layer featuring optical waveguides. The latter have exposed cores, which allow adiabatic coupling from tapered Si waveguides on the PIC to the polymer waveguides. The advantages of this optical coupling scheme are low insertion losses over a wide spectral bandwidth, together with relaxed assembly tolerances of ± 2 µm [8]. The broad operating wavelength range (> 100 nm) is particularly important for WDM applications. The combined electro-optical interface depicted in Fig 6b exhibits a high planarity guaranteeing a conformal contact with the PIC. Fig. 6c shows a fully assembled EOCB with a flip-chip bonded SiPh transceiver chip in place. This system successfully demonstrated the operation at a line rate of 50 Gbit/s per channel. Apart from the high-speed data transmission, the optics-based communication approach results in an estimated power consumption of only 5 pj/b [3]. Compared to a similar high speed electrical interconnect like Intel's QPI bus, this represents a reduction of 70%.

B. *ICT-QAMeleon*

Within QAMeleon, an EU funded R&D project, a next generation of SDN-programmable photonic components, modules and subsystems are developed. Both transceivers and WSS switches will be mainly based on indium phosphide (InP) chips [4]. In the case of the PIC based switches, an EOCB with electrical contacts and optical polymer waveguides was developed. A top-view microscopic image is shown in Fig. 7. The optical in-/outputs of the InP chips were connected to the polymer waveguides using butt-coupling and spot-size converters on the InP facets.

One of the WSS modules developed within QAMeleon relies on a hybrid InP-LCoS architecture, where the actual switching is performed by a LCoS, which is accessed through free space optics using micro-optical elements in. Within this LCoS WSS concept, so-called multimode interference couplers (MMIs) are used as wave-front-end (WFE) devices that transform the beam in order to be launched and received from free space [9]. WFEs in InP and polymer with splitting ratios of 1:4 and 1:5 have been manufactured and tested. Remarkably, the polymer-based devices have demonstrated a high channel uniformity with a difference of only 0.1 dB between the channels and a low insertion loss of 0.2 dB (excluding propagation losses) caused by the design [9]. While being employed as wave-front-ends for beam transforming applications within QAMeleon, these MMI structures can also be used as efficient and small-footprint light-routing devices. For example, a high power (laser-) input can be split this way within a photonic circuit, thus minimizing the number of necessary laser sources, and thereby enabling high integration density applications.

V. CONCLUSION

A high-performance EOCB platform based on planar polymer waveguide technology was presented. Its optical properties render it a suitable packaging solution for matching the gap between PICs and e.g. glass fibers. Measurements on the polarization behavior and on the operation at high optical powers confirm the robustness of the singlemode polymer waveguides. The benefits of this technology for PIC-packaging was shown and discussed using the example of the EU-funded projects ICT-STREAMS and ICT-QAMeleon. The demonstrated performance confirms the suitability of the polymer waveguide technology for a wide range of applications in PIC sensing and telecommunications and thus renders it a promising solution for next-generation chip-packaging.

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