Hybrid Polymer Integration for Communications, Sensing and Quantum Technologies from the Visible to the Infrared

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Abstract *We present concepts for transferring PIC building blocks from classical implementations in the C band towards shorter wavelengths. Exemplary functionalities include hybrid tunable lasers for 785 nm and 1064 nm, on-chip free-space sections for non-linear optics, and dielectric thin-film filters with 68 dB suppression.*

Introduction

Nowadays, photonics is used abundantly in a diverse array of applications, ranging from data transmission at highest speeds in communications networks to the sensing of tiniest signals in gravitational wave detectors. A key factor in the transfer of photonic solutions from lab-based demonstrators into deployed devices is the combination of various optical and optoelectronic functionalities on a single photonic integrated circuit (PIC).
In the past, the main drivers for the development of PIC platforms were applications in the classical telecommunications bands in the near infrared. This lead to the establishment of semiconductor-based platforms for monolithic integration, especially InP[1],[2] and silicon photonics[3]. In parallel, hybrid integration platforms for the combination of active elements with passive waveguiding platforms, notably silicon nitride[4], and polymers[5], were developed.
Monolithic integration approaches undoubtedly excel for PICs in which all required functionalities can be realized efficiently in a single material system since the complete chip can be fabricated at once. For other applications however, the hybrid approach has proven to be beneficial. It allows for the combination of elements from different material systems, each optimized for a specific function.
Over the last years, Fraunhofer HHI has developed the PolyBoard technology as a hybrid photonic integration platform based on single-mode polymer waveguides. It enables PICs with functional building blocks such as wavelength-tunable lasers[6], thin-film elements for spectral and polarization filtering[7], MMIs, AWGs as well as thermo-optic switches and variable attenuators[7]. While these functionalities were originally developed for the C band around 1550 nm, recent activities focused on the transfer towards shorter wavelengths by harnessing the flexibility of the hybrid integration approach.
This trend can also be seen for other hybrid integration platforms[8] and allows developing PICs for applications in the sensing and quantum technology domains that require specific wavelengths outside the classic telecommunications bands.

Tunable lasers for 785 nm and 1064 nm

An important building block of the PolyBoard platform in the C band is the hybrid tunable laser,

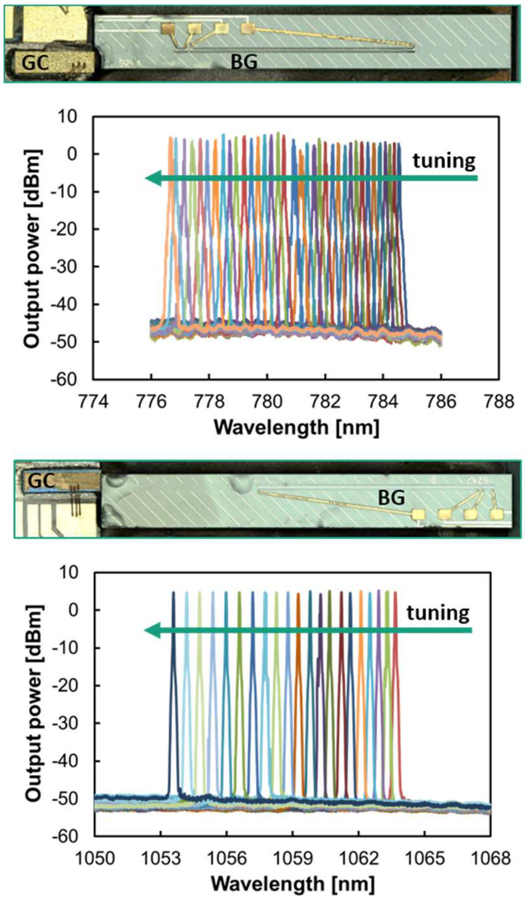

Fig. 1: Emission spectra of hybrid tunable lasers at 785 nm (top) and 1064 nm (bottom). The color-coded emission lines correspond to different operating points of the lasers. The microscope images show the hybrid integrated lasers consisting of GaAs-based gain chips (GC) and polymer-based Bragg gratings (BG).

which consists of an InP-based gain chip (GC) and a polymer waveguide chip.

The GC exhibits a broad emission spectrum around 1550 nm and features a high-reflective coated back facet. The front facet is anti-reflective coated against the polymer. This GC is coupled to the single-mode waveguide on the polymer chip that contains a corrugated waveguide Bragg grating (BG). It acts as a frequency filter for the broad spectrum emitted by the GC and reflects a narrow line. Hence, it serves as the second mirror of the laser cavity. Additional heating electrodes allow for the tuning of the phase and of the reflected wavelength by the thermo-optic effect. By setting the operating point of the laser appropriately, the emission wavelength is tunable by approx. 20 nm in the C band, and the emitted light is readily available for further processing on the PIC.

The hybrid laser approach described above is also feasible for the generation of shorter wavelengths, e.g. 785 nm and 1064 nm. These are prominent examples with wide use in sensing and non-linear optics. In monolithic PIC approaches, addressing these wavelengths would require to completely change the integration platform due to the limitations set by the band gap of the semiconductor material. The hybrid photonic integration approach, however, allows for the separate optimization of the BG and the choice of an appropriate GC.

Fabricated devices resulting from this optimization process are presented in Fig. 1. Here, GaAs-based GCs with emission spectra in the respective wavelength bands were used. On the polymer chip, the design of the corrugated Bragg grating was adapted to reflect the desired wavelength. By using the same integration concept as for the C band devices, tunable lasers at 785 nm [Fig. 1 (top)] and 1064 nm [Fig. 1 (bottom)] were realized, and tuning ranges of more than 8 nm (785 nm laser) and 10 nm (1064 nm) were demonstrated. Both devices exhibit stable operation with fiber-coupled optical powers well above 0 dBm and side mode suppression ratios greater 40 dB for all operating points. The maximum optical power was > 13 dBm for both lasers.

The presented lasers prove that the fabrication of efficient active components is feasible by the choice of suitable semiconductor chips and the redesign of the required passive functionalities on the polymer part. Compared to that, the integration of DFB lasers and photodetectors on hybrid PICs for shorter wavelengths is even more straightforward, because the coupling to appropriately designed waveguides on the PIC is sufficient.

Non-reciprocal and non-linear optics

While light generation, guiding, and detection are basic functionalities of every general-purpose photonic integration platform, the realization of non-reciprocal optical elements remains challenging. In recent years, a micro-optical bench approach was developed to accomplish this integration in the PolyBoard platform. Fig. 2 (top) shows a micrograph of a fabricated on-chip optical isolator. The light propagating through the waveguide is collected, collimated by a graded index (GRIN) lens and propagates through a free-space isolator consisting of polarization filters and a Faraday rotator. This isolator assembly is angled by 4° in order to minimize isolation-reducing interference effects. At the end of the free-space section, the light is collected by a second GRIN lens and focused to the output waveguide.

Fig. 2 (bottom) shows the transmission through the complete chip for the TE polarization (including fiber-chip coupling losses). From the

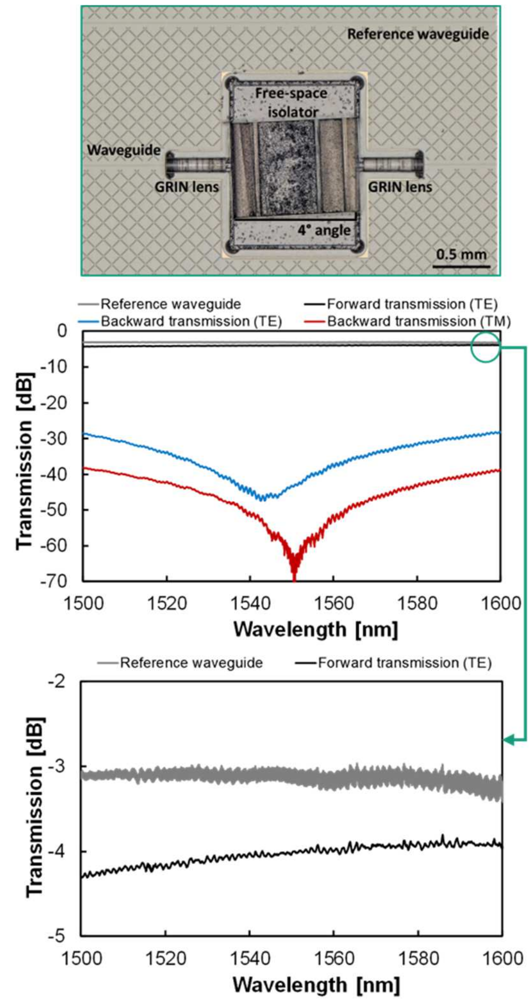

Fig. 2: Micrograph of an optical isolator integrated on a polymer-based PIC (top) and measured spectra of forward and backward transmission (middle). Magnification of the forward transmission spectrum (bottom).

comparison with a straight reference waveguide, an on-chip loss < 0.8 dB at a wavelength of 1550 nm is deduced. In the backward direction [Fig. 2 (middle)] the device efficiently blocks the light propagation with isolations of > 32 dB for TE and > 42 dB for TM polarization. One recently demonstrated use for this building block in the field of communications is the optical isolation of directly modulated tunable lasers from undesired back-reflections[9].

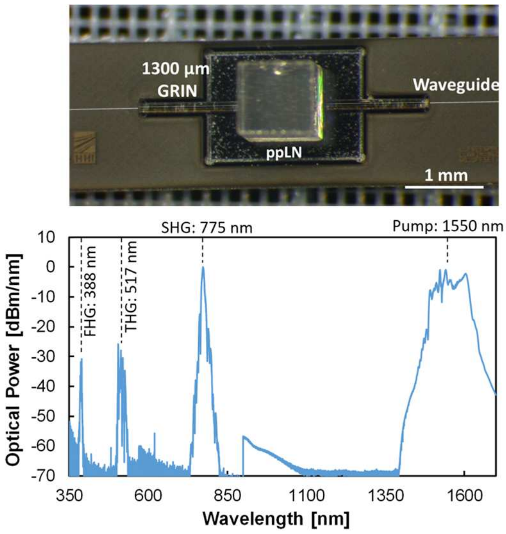

Fig. 3: Micrograph of a ppLN crystal integrated on a polymer-based PIC (top) and measured spectra of higher harmonics when pumped with an fs-pulse laser around 1550 nm (bottom) [10].

Despite having been developed for the integration of non-reciprocal elements for the C band, the micro-optical bench approach has recently found great use in shorter spectral bands as well, especially for the integration of non-linear optical crystals in on-chip free-space sections. Fig. 3 (top) shows a structure similar to the one presented in Fig. 2 (top), but using a periodically poled lithium niobate crystal. When pumped with a femtosecond laser (19 dBm optical power / 100 MHz repetition rate / 120 fs pulse duration) a spectrum as depicted in Fig. 3 (bottom) is emitted. Clearly visible are the peaks of the second, third, and fourth harmonic (SHG, THG, FHG) at 775 nm, 517 nm and 338 nm. The fiber-coupled SHG output power is as high as 8.2 dBm[10]. The broad spectral transparency of the polymer material allows for the collection, waveguiding and fiber coupling of all these wavelengths from the ultra-violet to the infrared. While SHG allows for generating light of shorter wavelengths on the PIC, the reverse process of spontaneous parametric down conversion (SPDC) can be used for the generation of single, heralded or entangled photons for quantum technologies.

On-chip dielectric filters

A challenge in the on-chip integration of SPDC processes is the handling of the pump light, which may contaminate the single photon output. In classical free-space optics, dielectric coatings of optical elements are used for the suppression of the undesired wavelengths.

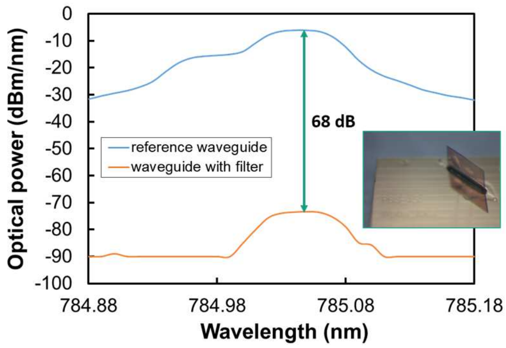

Fig. 4: Transmission through a waveguide with TFF for the suppression of 785 nm light compared to a reference waveguide without filter. The inset shows an exemplary PIC with inserted dielectric TFF.

In the PolyBoard platform, thin-film filters based on dielectric layer stacks are a standard building block for polarization and wavelength handling in the C band[7]. Because they are fabricated on wafer-scale and later inserted into etched slots perpendicular to the waveguides, the layer stack can easily be adapted for the desired functionality and wavelength band. Fig. 4 shows the transmission through a PolyBoard waveguide with a 785-nm pump-blocking filter as one example of this approach. Here, 68 dB pump suppression was achieved at <1 dB excess loss for the photons generated in the C band. Combining a 775 nm tunable laser with a non-linear crystal for SPDC and a TFF-based pump suppression could therefore enable an efficient PIC-based source of heralded single photons at 1550 nm.

Conclusions

Hybrid photonic integration offers ways to flexibly adapt existing PIC building blocks for new wavelength bands to allow for the efficient generation, guiding and detection of light across broad spectral ranges. This allows for the transfer of know-how from well-developed PICs for telecommunications into emerging applications in the fields of sensing and quantum technologies.

Acknowledgements

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