# A hybrid photonic integrated signal source with >1.5 THz continuous tunability and <0.25 GHz accuracy for mmW/THz applications

*(Student paper)*

**Tianwen Qian, Peer Liebermann, Martin Kresse, Klara Mihov, Jakob Reck, Madeleine Weigel, Moritz Kleinert, Crispin Zawadzki, David de Felipe, Norbert Keil and Martin Schell**

Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, HHI, 10587 Berlin, Germany
tianwen.qian@hhi.fraunhofer.de

**We present a hybrid photonic integrated mmW/THz signal source, which comprises two tunable lasers and on-chip wavelength meters. The continuous wavelength tunability of a single laser is over 12 nm (1.5 THz), and the wavelength meter accuracy is below 0.002 nm (0.25 GHz) over the entire C-band.**
***Keywords***: *hybrid integration, tunable laser, continuous tuning, continuous wave terahertz*

## INTRODUCTION

Using the optical heterodyning technique to generate continuous wave (CW) electrical signals with frequencies ranging from the millimeter range (from 67 GHz to 300 GHz) to the terahertz range (above 300 GHz) is a simple and straightforward method enabling the mmW/THz applications [1–3]. With two optical wavelengths that are mixed on a photodiode, the electrical beat signal generated at the output is only limited by the bandwidth of the photodetector. Besides, in order to control the generated mmW/THz frequency, it is mandatory to know the absolute value of the two wavelengths and achieve mode-hope-free tuning within the target frequency range.

In this paper, we present an mmW/THz signal source based on a hybrid photonic integrated circuit (PIC), which comprises two hybrid tunable DBR lasers for the generation of optical signals. These signals are used for the photonic generation of the mmW/THz signals. The tunable laser provides continuous tuning over 12 nm in the C-band. Additionally, on-chip wavelength meters are implemented on the PIC using thin-film filters (TFF), etalons, and PDs allowing for on-chip read-out of the laser wavelength.

## DESIGN AND THEORY

Fig. 1 shows the design of such a signal source, as well as the fabricated and assembled PIC based on Fraunhofer HHI's hybrid photonic integration platform PolyBoard [4, 5]. Starting from the left-hand side, an InP chip with two active sections bonded on an AlN submount is butt-coupled to the polymer chip. After each active section, the PolyBoard chip comprises thermo-optically tunable phase shifters and Bragg gratings to implement two tunable distributed Bragg reflector (DBR) lasers. In the central part of the PIC, thermo-optically tunable phase shifters allow for phase tuning of the generated optical signals. Additionally, variable optical attenuators (VOAs) have been included in order to allow for equalization of the amplitude of the two signals generated by the tunable lasers. On the right-hand side of the chip, U-grooves are placed to connect the fibers directly. Finally, the upper and lower parts of the PIC feature power-monitor photodiodes (PD-MO) and wavelength meters. The wavelength meter comprises a pre-etched slot for the insertion of a TFF which shows a monotonic frequency dependence, and U-grooves with different lengths to insert coated GRIN lenses for the implementation of the two etalons.

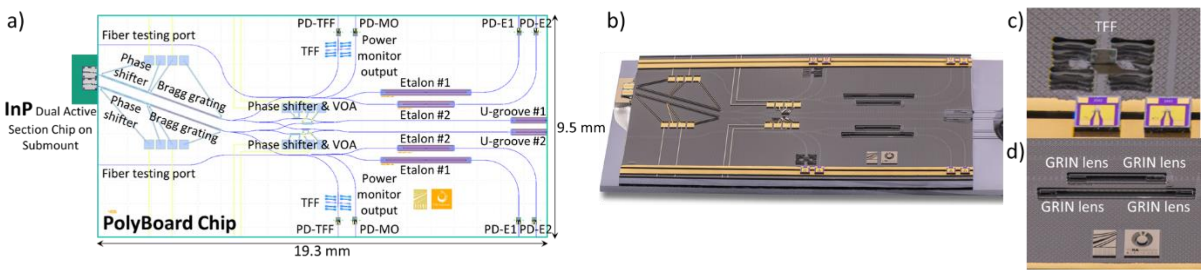


*Fig. 1. Fiber-coupled THz signal source containing assembled PDs, TFFs, etalons, and butt-coupled with InP dual active section chip. a) GDS design of such PIC. b) Assembled PIC coupled with fibers fixed on Si-carrier. c) TFF inserted in the pre-etched slot and PDs mounted on the top surface of the PolyBoard. d) Coated GRIN lenses form two etalon structures inserted in the U-grooves.*

A key requirement in the design is that the tunable lasers allow for continuous tuning. By scanning through the grating and phase section heating currents, Fig. 2 a) shows the wavelength mapping of such a laser. The solid lines show the mode-hop boundaries between adjacent modes, and the dashed line marks a trajectory possible for continuous tuning. In this work, the target frequency sweep amounts to 3 THz, which is equivalent to a wavelength range of 24 nm in the C-band. This implies that, if each tunable laser is tuned counter-directionally in order to achieve a difference in the wavelengths of up to 24 nm, each of them has to be tuned 12 nm continuously. In order to allow for continuous tuning, the use of long phase shifters is necessary to avoid mode-hops [6]. In Fig. 2 b), the calculated tuning range with varying lengths of the phase shifter is shown. As can be seen, for a phase section length of 2 mm, 12 nm continuous tuning can be achieved. The Bragg gratings have been designed to ensure single mode operation in the resulting cavity length.

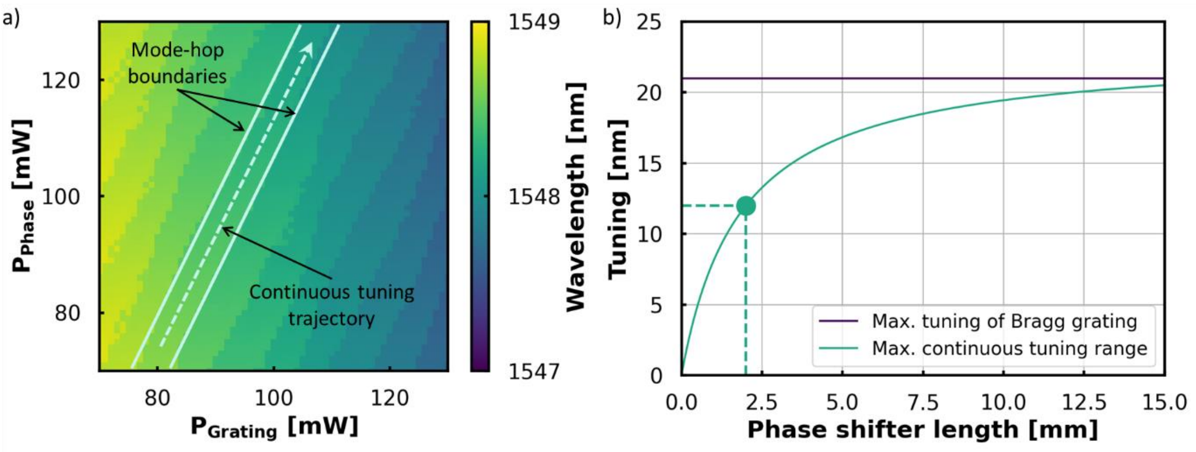


*Fig. 2. a) Wavelength mapping retrieved by scanning the grating and phase section heating currents of the tunable laser. The solid lines show the mode-hop boundaries, and the dashed line marks a possible trajectory for continuous tuning. b) Calculated tuning range with varying phase shifter length. The marked green dot indicates the target 12 nm tuning range resulting in a 2 mm phase section length.*

The working principle of the on-chip wavelength meter has been reported in [7]. In this design, two etalon structures with different free spectral ranges (FSR) have been implemented to allow exploring the Vernier effect and ensure a higher resolution of the wavelength determination. As can be seen in the exemplary plot in Fig. 3, firstly, the wavelength is roughly determined through the edge filter, which indicates two other photocurrents on the corresponding curves of the two etalon structures. Secondly, by comparing the slopes of these two etalon curves, the one with a steeper slope is used to determine the wavelength, since the steeper rising or falling slope enhances the accuracy of the wavelength determination.

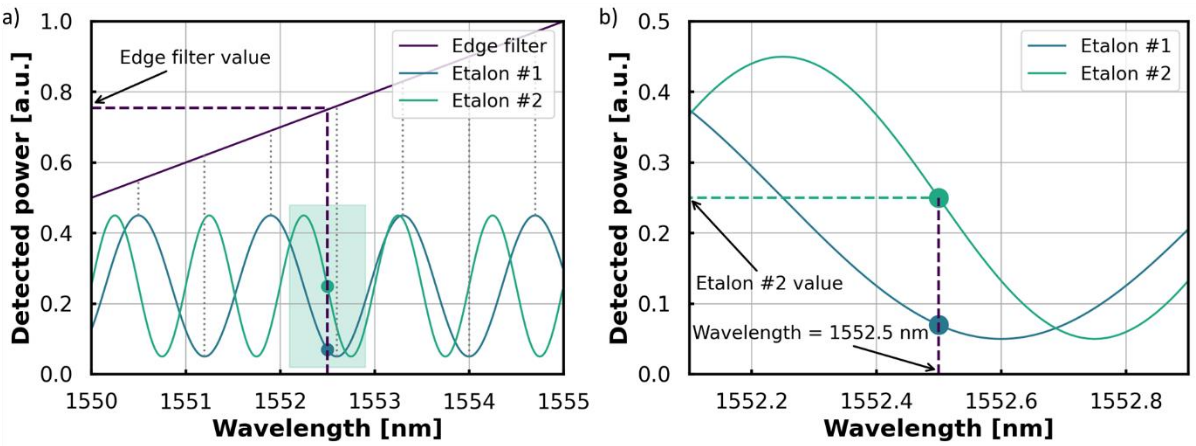


*Fig. 3. Exemplary detected power versus wavelength after the edge filter and two etalons. a) The edge filter is used for coarse wavelength determination, which indicates two other values on the corresponding etalon curves. b) The one with a steeper slope is used to determine the wavelength by evaluating the two etalon curves.*

**RESULTS**

The continuous tuning test and wavelength meter test have been conducted individually. Continuous tuning algorithms following the trajectory between mode-hop boundaries have been developed. The test is done on the single tunable laser test structure, which has the same parameter as on the PIC and is fabricated on the same wafer. By simultaneously driving the Bragg grating and the phase shifter, Fig. 4 a) shows the retrieved wavelength with increasing driving steps. As can be seen, a continuous wavelength tuning range of 14.3 nm has been achieved. With each one of the two lasers of the PIC being tuned over the 12 nm (1.5 THz) range, targeted 3 THz frequency sweeps could be achieved. Moreover, the wavelength read-out algorithms for determining the slope of the etalon curves were developed, and wavelength read-out tests were performed. For these tests, an optical signal of 0 dBm from an external tunable laser source was coupled into the fiber testing port, followed by a wavelength meter consisting of an edge filter and two etalons with slightly varied FSR (Etalon #1: 51.37 GHz, Etalon #2: 50.85 GHz). In Fig. 4 b), the measured wavelength on the on-chip wavelength meter versus the set wavelength on the external tunable laser is plotted, showing that a good agreement has been reached between the retrieved and the target wavelength. Fig. 4 b) also shows the read-out deviations from the target wavelength. Over 99% of the measurement points show a deviation lower than 0.05 nm, which corresponds to an average deviation less than 0.002 nm, in the C-band corresponds to an error in the frequency read-out lower than 0.25 GHz.

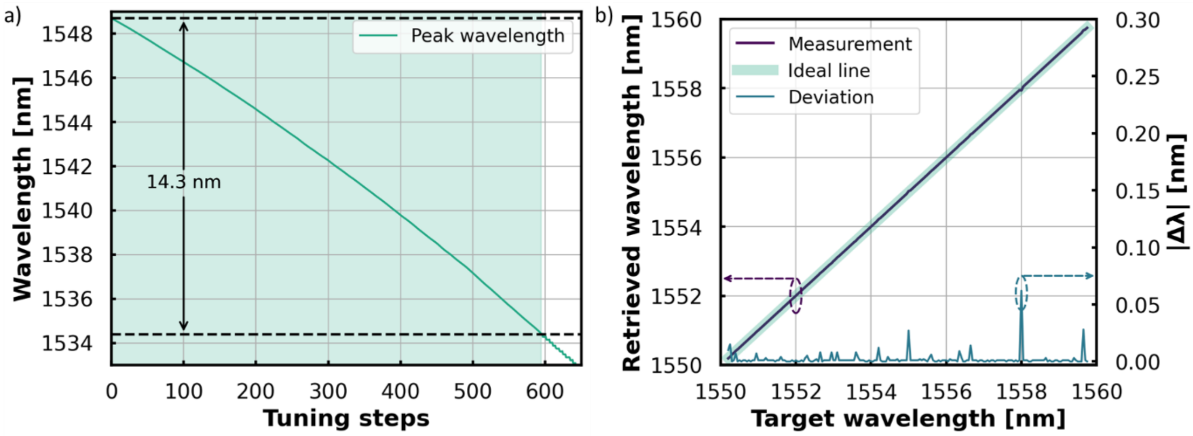


*Fig. 4. a) Continuous tuning of 14.3 nm is achieved by driving the Bragg grating and phase shifter simultaneously, following a trajectory between the mode-hop boundaries. b) Wavelength meter test with two etalon structures shows the enhanced resolution with an average deviation below 0.002 nm, which corresponds to 0.25 GHz in C-band.*

**CONCLUSION**

We successfully demonstrated a fiber-coupled photonic hybrid integrated mmW/THz signal source, which comprises two hybrid continuous tunable DBR lasers and on-chip wavelength meters. The continuous tunability of the laser is over 12 nm (1.5 THz), by combining both lasers, a 3 THz continuous tuning range could be achieved. Additionally, the on-chip wavelength meters implement two etalon structures and the enhanced accuracy reaches below 0.002 nm (0.25 GHz) over the entire C-band. The above-demonstrated work paves the way for future mmW/THz applications.

Acknowledgments: This work was partly financed by the European Union’s Horizon 2020 Research and Innovation Programme, in the framework of the TERAmeasure project (Grant agreement ID: 862788).

**References**

[1] T. Nagatsuma, G. Ducournau, C. C Renaud, *Advances in terahertz communications accelerated by photonics,* Nat. Photon., vol. 10, no. 6, pp. 371-9, 2016.

[2] G. Carpintero, S. Hisatake, D. de Felipe, R. Guzman, T. Nagatsuma, N. Keil, *Wireless Data Transmission at Terahertz Carrier Waves Generated from a Hybrid InP-Polymer Dual Tunable DBR Laser Photonic Integrated Circuit,* Sci. Rep., vol. 8, no. 1, pp. 1-7, 2018.

[3] T. Qian, M. Deumer, Y. D Gupta, S. Nellen, B. Schuler, H. Conradi, M. Kresse, J. Reck, K. Mihov, M. Kleinert, M. Weigel, C. Zawadzki, D. de Felipe, B. Globisch, M. Baier, N. Keil, M. Schell, *Hybrid Polymer THz Receiver PIC with Waveguide Integrated Photoconductive Antenna: Concept and 1st Characterization Results*, in Proceedings of the Optical Fiber Communication Conference (OFC) 2022, pp. W3D.6, 2022.

[4] D. de Felipe, M. Kleinert, C. Zawadzki, A. Polatynski, G. Irmscher, W. Brinker, M. Moehrle, H.-G. Bach, N. Keil, M. Schell, *Recent Developments in Polymer-Based Photonic Components for Disruptive Capacity Upgrade in Data Centers,* J. Lightwave Technol., vol. 35, no. 4, pp. 683-9, 2017.

[5] M. Kleinert, M. Nuck, H. Conradi, D. de Felipe, M. Kresse, W. Brinker, C. Zawadzki, N. Keil, M. Schell, *A platform approach towards hybrid photonic integration and assembly for communications, sensing, and quantum technologies based on a polymer waveguide technology*, in Proceedings of the 2019 IEEE CPMT Symposium Japan (ICSJ), pp. 25-30, 2019.

[6] D. de Felipe, M. Happach, S. Nellen, W. Brinker, M. Kleinert, C. Zawadzki, M. Möhrle, N. Keil, T. Göbel, K. Petermann, M. Schell, *Hybrid polymer/InP dual DBR laser for 1.5 µm continuous-wave terahertz systems*, in Proceedings of the SPIE OPTO, pp. 195-201, 2016.

[7] A. Schoenau, T. Qian, P. Liebermann, C. Kastner, H. Conradi, M. Kresse, D. de Felipe, M. Baier, N. Keil, M. Schell, *Hybridly Integrated Photonic Integrated Circuit for Wavelength and Polarization Determination*, in Proceedings of the 2022 European Conference on Integrated Optics (ECIO), pp. W.B.3, 2022.