Photonic Integrated Circuits for Terahertz Communication: The Hybrid Integrated Microwave Photonic approach

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Abstract: Optical heterodyne signal generation is the most flexible photonic microwave generation technique. Photonic integrated solutions have been shown monolithically on InP, and more recently on silicon. We present novel implementations using hybrid integration technology with silicon nitride (with high-Q resonators for extremely low linewidth) and polymer (with low permittivity material for highly efficient radiation).

1. Introduction

1.1. Optical heterodyne signal sources

Over recent years, network forecasts have warned about explosive growth in wireless data traffic due to the ever-increasing demand for higher data rates in mobile communications, urging to increase their data capacity [1]. The total bandwidth currently allocated in the microwave range (3 to 30 GHz) is insufficient, with bands having a few MHz bandwidths. Researchers and industries have demonstrated the potential of the millimeter-wave range (30 GHz to 300 GHz), with regulatory bodies allocating wider regions of the spectrum for wireless communications. A key milestone was the 2008 Japan's NTT demonstration using a wireless link at 120 GHz carrier frequency to provide live TV coverage of the 2008 Beijing Olympics [2], which served to kick opening access to spectrum above 100 GHz by regulators. In 2014, Japan allocated the 116 -134 GHz band to accommodate such service, and more recently (March 15, 2019), the US Federal Communications Commission (FCC) voted to allow access to spectrum above 100 GHz for the first time freeing 21.2 GHz for unlicensed use at 116-123 GHz band, 174.8-182 GHz band, 185-190 GHz band, and the 244-246 GHz band [3]. This trend has been followed in Europe, where on January 17, 2020, UK Office of Communications (Ofcom) started the process to allow using parts of 100-200 GHz [4].

Microwave photonics has significantly contributed to push the technological boundaries in wireless communications, especially with regard to accessing the millimeter-wave range above 100 GHz and reaching real-time transmission data-rates above 10 Gb/s [5]. Among the available techniques for continuous-wave (CW) signal generation, optical heterodyning provides the widest continuous tuning range, with the potential of covering from the microwave range all the way into the Terahertz. Optical heterodyning is based on the principle of mixing two optical wavelengths (λ_1, λ_2) onto a photomixer (either a high-speed photodetector or photoconductor) producing an RF frequency (f_{RF}) defined by the difference frequency ($f_{RF} = |\lambda_1 - \lambda_2|$). To date, most demonstrations rely on discrete photonic components with fiber optic interconnections, which makes them sensitive to ambient factors, limiting their energy-efficiency, flexibility and scalability. This approach negatively impacts the RF signal stability since the lasers behave as uncorrelated noise sources (affecting the RF signal phase noise) and use independent thermal control (affecting the frequency drift of the signal).

1.2. Integrated Microwave Photonics Approach

Enabling to place two single-frequency wavelength-tunable (distributed feedback -DFB- or distributed Bragg reflector -DBR-) semiconductor lasers and combine their wavelengths on a single chip, photonic integration technology became a promising new approach to address the above issues of optical heterodyne sources. Regarding the stability, it was suspected that with the two laser sources on the same chip, both would experience the same environment fluctuations reducing the drift, and being the distances shorter, would improve the effectiveness of optical phase locked loop schemes [6].

Using monolithic integration on Indium Phosphide (InP), a full millimeter-wave transmitter including two DFB lasers, 2x2 Multimode Interference (MMI) couplers, Semiconductor Optical Amplifiers (SOAs), Electro-Absorption

Modulators (EAM) and Uni-Travelling Carrier Photodiodes (UTC-PD) was achieved [7]. In this approach it was difficult to optimize the epitaxial layer stack since had to fulfill the requirements for so many different types of components. The results showed 1.5 nm (~ 188 GHz) wavelength tuning range for each DBF laser and optical linewidth greater than 1 MHz, a figure that is common for this type of devices.

2. Hybrid Integrated Optical Heterodyne Sources

In order to optimize each component of the integrated microwave photonic transmitter free of the compromises imposed by the monolithic approach, hybrid integration technology is required. Hybrid integrations allows to combine chips from different material platforms. It is mandatory that one chip be on InP to provide for optical gain while the rest of functionalities can be implemented on another material. One approach reported a photonic microwave generator on a heterogeneous silicon-InP platform [8], in which the InP chip is bonded directly onto the silicon. The optical heterodyne source is implemented through the integration of a couple of laser structures using ring filters in different configurations so select a single emission wavelength. Additionally, resistive heater structures over the rings enable active tuning of the emission wavelength over a wide frequency range, demonstrating signal generation from 1 to 112 GHz.

In this paper we compare two alternative hybrid integrated approaches with significant advantages. On one hand, we analyzed the hybrid integrated InP-Si_3N_4 platform at LioniX International integrating two hybrid lasers with intracavity wavelength selective optical filters with high optical power (<100 mW), wide wavelength tuning (>100 nm) and narrow optical linewidth (< 25 kHz)[9]. Continuous-wave generation of RF frequencies over a wide tuning range from C-band (4 GHz – 8-GHz) to W-band (75 GHz – 110 GHz) is achieved with record low RF electrical linewidth around 108 kHz and long-term drift < 12 MHz with two free-running lasers. On the other, we have analyzed C-band optical heterodyne sources in a hybrid integrated polymer-InP platform, Polyboard from the Hybrid PIC group at Fraunhofer Heinrich Hertz Institute [10]. This approach has the advantage of using the high thermo-optic coefficient of polymer materials to yield a large wavelength tuning, which enables generating THz signals over a wide range (> 2 THz). Previous approaches have in common the disadvantage of locating the photodiodes over a high refractive index material, which introduces high losses in the RF signal and which makes it difficult to radiate the generated RF wave into the air, extracting it from the material.

	InP [7]	Silicon on Insulator [8]	Silicon Nitride [9]	Polymer [10]
Integration approach	Monolithic InP	Heterogeneous silicon-InP	Hybrid SiN-InP	Hybrid polymer-InP
Optical linewidth	> 1 MHz	148 kHz	< 25 kHz	< 200 kHz
RF Tuning range	1 to 115 GHz	1 to 115 GHz	1 to 112 GHz	1 GHz to 2 THz

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