Recent Progress and Future Prospect of Photonics-Enabled Terahertz Communications Research

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SUMMARY This paper reviews a recent progress in terahertz wireless communications enabled by photonics technologies. After briefly summarizing transceiver configurations with electronics and photonics technologies, photonics-based approaches to achieving over 100-Gbit/s data rates are discussed. Then, some of our updated results on real-time wireless transmission experiments using discrete components are shown at data rates up to 50 Gbit/s. Finally, integration technologies are described by demonstrating latest advances in integrated optical sources and transmitters.

key words: terahertz, communications, photonics, integration

1. Introduction

The data rate of wireless communications has been increasing in order to catch up with that of wired and/or fiber-optic communications. The prospective data rate for wireless communications in the marketplace will be 100 Gbit/s within 10 years [1], [2]. To enable such data rates, there has been a growing interest in the use of terahertz (THz) waves, whose frequencies range from 100 GHz to 1 THz, for broadband wireless communications [1], [3]–[6]. Particularly, above 275 GHz, there is a possibility to employ extremely large bandwidths for “radio” communications, since these frequency bands have not yet been allocated at specific active services, and standardization efforts have been becoming very active [1], [7].

Figure 1 summarizes experimentally achieved data rates of over 1 Gbit/s by transmission experiments with over-100-GHz carrier frequencies at 100–150 GHz [8]–[14], 200–250 GHz [15]–[21], 300–350 GHz [22]–[31], 400–450 GHz [23], [32], 500–700 GHz [27], [33]–[35]. Data points with triangles are demonstrations using electronics-based transmitter, while data points with circles are achieved by photonics-based ones. Filled and open marks denote data measured with a real-time transmission experiment, and with off-line digital signal processing, respectively. The electronics-based approach now enables most of the 100-150-GHz band wireless links. From 200 GHz to 400 GHz, the photonics-based approach is pushing the front of research with respect to the data rate. Above 500 GHz, the data rate still stays low, due mainly to the lack of power emitted from the transmitter.

In this paper, Sect. 2 starts by providing an overview of building blocks of transmitters and receivers for THz communications. In the following section, we show our recent system demonstrations using discrete components such as frequency-tunable lasers, optical modulators, photodiodes as well as diode detectors and mixers. Finally, in Sect. 4, we discuss the advances that have been reported using photonic integration technologies to make the system more compact, cost-effective and energy-efficient.

2. Building Blocks

2.1 Transmitters and Receivers

Figures 2 and 3 show schematic diagrams of a transmitter and a receiver, respectively. THz communications research was initiated with use of photonic techniques for signal generation and modulation as shown in building blocks of the photonics-based transmitter of Fig. 2 (b). Comparing to the all-electronic transmitter of Fig. 2 (a), it has proven to be effective to achieve spurious-free carrier signals [36] and higher data rates of over 20 Gbit/s. This could be realized thanks to the availability of telecom-based high-frequency components such as lasers, modulators and photodiodes (O-E converters). The use of optical fiber cables enables us to distribute high-frequency RF signals over long distances, and makes the size of transmitter frontends compact and light. Moreover, ultimate advantage of the photonics-based...
Fig. 2 Configuration of transmitters based on electronics (a) and photonics (b). RTD: resonant tunneling diode, EOM: electro-optic modulator, EAM: electro-absorption modulator, EDFA: Erbium-doped fiber amplifier, SOA: semiconductor optical amplifier.

approach is that wired (fiber-optic) and wireless communication networks could be connected seamlessly in terms of data rates and modulation formats.

As for receivers, all electronic approaches of Figs. 3 (a) and (b) have usually been adopted even with the photonics-based transmitter. The photonics-based receiver has also been reported by using a photodiode as a photonic downconverter [37], [38] (Fig. 3 (c)).

As we have seen in the development of 120-GHz-band wireless links, the photonics-based transmitters have been replaced with all-electronic ones. Here, we briefly describe a recent progress of electronic devices and circuits. At frequencies above 100 GHz, GaAs and InP devices and integrated circuits (ICs) have been key players in all-electronic THz communications research, because of high cut-off and maximum frequencies of transistors [8]–[10], [18], [20], [33], [39], [40]. Si-device technologies have started to reveal their potential in these 2-3 years [11], [12], [41], [42]. A power combining technique using integrated array antennas has proven to be effective to increase an output power in Si-CMOS transmitter ICs [43], [44]. According to the ITRS roadmap, the half pitch of the wiring in Si-LSIs is expected to become 10–12 nm by 2020, enabling the maximum operation frequency of the mass-production level of Si-CMOS devices reach 1 THz, as well as various RF ICs in excess of 300-GHz operation could be realized in Si-CMOS. GaN and InP ICs, however, have the ability to significantly surpass Si devices in terms of the break-down voltage, and are indispensable in applications where a high output power is required. Ultimate terahertz ICs would be a fusion of compound semiconductor and Si semiconductor ICs.

Moreover, unique THz electronic devices utilizing the plasma-wave effect in field-effect transistors [45]–[47] and the resonant tunneling effect [30], [33], [48], [49] have attracted much interest, because they can be operated as both transmitters and receivers.

2.2 Optical Signal Generators

In the photonics-based system, the optical signal generator, whose intensity is modulated at THz frequencies, is one of the key building blocks as shown in Fig. 4.

Most common optical continuous wave (CW) signal generator with THz frequencies is based on an optical heterodyning, using a dual wavelength optical source. In this technique, two optical wavelengths $\lambda_1$ and $\lambda_2$ are mixed on a photodiode or a photoconductor to generate an electrical beat note with its frequency being determined by the difference of the two optical wavelengths, $f_{\text{beat}} = c|\lambda_1 - \lambda_2|/(\lambda_1 \cdot \lambda_2)$. There are different solutions to implement the dual wavelength source. The most straightforward source involves combining the light from two different
single-frequency semiconductor lasers (Fig. 4(a)). While its main advantage is the broad tuning range of frequency, the weakness is that the frequency stability is generally poor, requiring locking techniques for the two optical wavelengths [50].

One way to achieve stable signals is to use an external optical modulator driven by an electronic RF source (Fig. 4(b)). When an optical intensity modulator is used after a CW single-frequency semiconductor laser, side-bands around the optical wavelength is generated, being spaced by the modulation frequency applied to the modulator. By adequately selecting the modulator operating point, double-sideband suppressed carrier (DSB-SC) generation can be achieved. This suppresses the central optical carrier, leaving the sidebands separated by twice the modulation frequency. Higher order harmonics can be achieved cascading modulators [51]. In this case, optical filters such as arrayed waveguide gratings (AWGs) and other tunable filters should be used to select only two of harmonic components showing optical frequency comb signals (Fig. 4(c)).

Another optical CW signal generator with THz frequencies is based on optical pulsed sources. The output of the semiconductor laser is a continuous stream of pulses, spaced in time by the inverse of the repetition frequency, \( f_{rep} = c / 2n_d L \), where \( n_d \) is a refractive index of the laser active layer, and \( L \) is a cavity length of the laser. The optical spectrum is a comb of modes, spaced by this frequency. The main characteristic is that each of the modes is locked in phase to the adjacent ones. In the THz signal generation, the repetition frequency determines the fundamental frequency of THz signals when the pulse train is fed to the O-E converter. Higher harmonics can also be used when optical filters are placed before the O-E converter.

There are two types of semiconductor sources that can generate pulses. One is a passively mode-locked (PML) laser diode, where a saturable absorber (SA) section is integrated in the semiconductor laser to lock the phase of each mode (Fig. 4(d)). This technique produces an optical pulse train only with a DC bias supply, which relaxes an electrical bandwidth requirement significantly. Passive colliding pulse mode-locked (CPM) laser structures enable optical multiplication of the repetition rate at frequencies from 40 GHz to 500 GHz [51]. The frequency stability improves as the length of the SA reduces. The other is a hybrid mode-locked (HML) laser diode (Fig. 4(e)). Main feature of this scheme is that the SA section is electrically modulated, allowing a synchronization between the stream of optical pulses and the system clock. It also reduces the timing jitter, just transferring the phase noise characteristics of the RF oscillator to the pulse train [53].

The most straightforward approach to implement these signal generation schemes is to assemble the required discrete components. However, the optical fiber connections that are required introduce many problems, including path length variations due to thermal variations. A novel approach, that is becoming readily available nowadays, is to use photonic integration techniques [54]. Photonic integration allows placing all of the required components onto a single chip. This has several advantages, starting from eliminating fiber coupling losses among the different components. Details will be discussed in Sect. 4.

3. Discrete Systems and Demonstrations

3.1 Direct Detection System

Figure 5 shows a block diagram of the experimental set up to evaluate the wireless link based on intensity modulation and direct detection scheme using the transmitter building block scheme on Fig. 2(b) with the optical signal source on Fig. 4(a) and receiver based on Fig. 3(a). The beat note of optical signals is generated by two free-running lasers with a wavelength difference of 2 nm to be converted to THz waves at 330 GHz by the photodiode. For the modulation, an electro-optic intensity modulator (EOM) driven by electrical data signals from a pulse-pattern-generator is used to perform an amplitude-shift-keying (ASK) modulation up to 50 Gbit/s. The modulated optical signal is amplified by an Er-doped fiber amplifier (EDFA), and finally fed to the waveguide-mounted uni-travelling-carrier (UTC) photodiode [55].

THz waves radiated from the horn antenna (25-dBi gain) are collimated by a dielectric lens (2-inch diameter) in the transmitter. Propagated THz waves are focused by another lens to the horn antenna of the receiver. The total antenna gain is about 40 dBi. The distance between the transmitter and receiver is 0.5 ~ 1 m, where there is little change in the received power and a multi-path effect is negligible in the experiment.

The data signal is demodulated by a Schottky-barrier diode (SBD) detector which is mounted on a WR-2.8 waveguide structure. A 3-dB baseband bandwidth of the detector is 37 GHz. The responsivity of the SBD detector is 2000 V/W. The SBD detector works based on a square-law detection up to the input power level of 100 \( \mu \)W. The output baseband signal is amplified by a 38-GHz pre-amplifier and reshaped by a 35-GHz trans-impedance amplifier used as a limiting amplifier.

Figure 6 shows a bit error rate (BER) characteristic of the link and an eye diagram of the demodulated signal in the receiver at 50 Gbit/s. Error-free (BER < \( 10^{-11} \)) has been
confirmed at a transmitter photocurrent of 6.7 mA, which corresponds to the transmitted power of 90 μW. This bit rate might be the highest achievable when we consider bandwidths of all the electronic components such as amplifiers including our BER test equipment. By using a polarization multiplexing scheme with wire-grid polarizers, it is possible to double the bit rate to 100 Gbit/s [27].

3.2 Coherent Systems

With RF amplifier-less systems, the coherent link is effective to increase a sensitivity of the receiver, which enables an extension of transmission distance.

In the transmitter, the carrier frequency and phase are stabilized with a configuration of Fig. 4 (c), while the receiver configuration is based on that of Fig. 3 (b) with a sub-harmonic diode mixer driven by the local oscillator signal with a half frequency of the carrier. Figure 7 shows a detailed block diagram of the coherent link system. As for the optical frequency comb generation, we used two electro-optic phase modulators (PM) driven by 25-GHz sinusoidal signals to generate sidebands of over 400-GHz width. We also optimized the amplitude and phase of 25-GHz signals applied to each modulator to maximize the intensity of “two” optical carriers separated at 300 GHz (12x25 GHz). By using a programmable optical filter and combiner based on the Liquid Crystal on Silicon (LCoS) technology, we selected and combined the two optical carriers. The coherent detection receiver using the SBD mixer has an overall 3-dB baseband bandwidth of 38 GHz. The sensitivity of the coherent detector is typically 20 dB higher than that of the direct detector, although the total receiver sensitivity is dependent on RF and baseband bandwidths for the designated data rate.

We performed a 20-m distance transmission experiment using the coherent system. In the transmission experiment, THz beams radiated from the horn antenna are collimated by aspheric dielectric lenses (100-mm diameter) over the link distance of 20 meters. Simulated gain of such a lens antenna structure is 50 dBi. To perform a proper bit-error-rate (BER) testing enabling the clock synchronization between the pulse pattern generator and the BER tester, we constructed a round-trip link configuration as shown in Fig. 8.

Figure 9 shows a BER characteristic and an eye diagram showing real-time error-free transmission at 30 Gbit/s at 20-m link distance.
corresponds to \(\sim 100\,\mu\text{W}\) output power of the transmitter, while error-floors were observed at 40 Gbit/s and 50 Gbit/s.

There are several reasons for this limitation. The most significant one is considered to be a decrease in the received power. The second one is caused by the mismatch of center frequency of the transmitter and receiver, where the output power and sensitivity, respectively, become maximum. We believe that better performance with respect to the BER characteristics should be obtained by solving these issues.

Currently, we are developing the coherent system with other modulation format like QPSK to increase the data rate up to 100 Gbit/s, and the massive arrays of photodiode to increase the link distance by enhancing the output power of the transmitter up to 10 mW.

4. Photonic Integration Technologies

4.1 Integration Platforms

A Photonic Integrated Circuit (PIC) is a chip that has more than two functional blocks connected through an optical waveguide. The functional building blocks that are required for photonic-based terahertz communications are a photonic signal source, a data modulation, and an optoelectronic converter.

These building blocks can be realized using different integration technologies, having equivalent functionality. One key technological decision is the material system to use, being Group III-V materials and the Group IV materials the most relevant ones [54]. The first group is mainly represented by Indium Phosphide (InP), while the second group involves all the varieties of Silicon, from Silicon on Insulator (SOI), Silica on Silicon (SiO\(_2\)/Si) or Silicon Nitride (Si\(_3\)N\(_4\)/SiO\(_2\)), which are broadly known as Silicon Photonics.

III-V materials have a direct band gap, enabling active waveguide sections at which optical gain is produced under current injection. This is a key characteristic to develop efficient semiconductor lasers. In addition, this material has different quaternary alloys that provide a wide range of optical characteristics. This enables offering also transparent optical waveguides on InGaAsP for optical interconnects and other basic functional components such as multimode interference (MMI) couplers or arrayed waveguide gratings (AWG). Active-passive photonic integration involves the development of optical junctions between active and passive waveguide sections. The different layer structure between the active and the passive waveguides introduces coupling losses (usually \(< 0.1\,\text{dB/junction}\)) as well as back-reflections (\(< -40\,\text{dB}\)).

The possibility to combine active and passive sections on InP allows this material to offer monolithic integration, in which all the components are integrated on the same chip, without joints of seams. Monolithic integration provides lower final cost due to less assembly and testing, smaller size, higher reliability, and enhanced performance. The most serious drawbacks are the significant performance trade-offs that are required among the different components, as well as the back-reflections at the active-passive transitions.

Si-based integration platforms main drawback is that these do not have a direct bandgap, and therefore do not emit light efficiently. Silicon platforms allow integrating passive components only. One of its key advantages is the mechanical strength, which has enabled using wafer diameters above 300-mm to increase the yield and reduce the cost. The other is that Silicon has a high-quality native oxide with extremely low optical propagation losses (\(< 0.003\,\text{dB/cm}\)). In addition, being Silicon the integration material for electronics, it is being tackled the issue of using Silicon as common platforms for photonics and electronics.

Recently, a radical step forward has been achieved in photonic integration establishing generic integration platforms [56], in an effort to make photonics systems cheaper and ubiquitous, providing Multi-Project Wafer (MPW) runs, sharing the fabrication costs among several users.

4.2 Integrated Laser Sources

In this section we present different monolithically integrated semiconductor laser structures specifically designed to serve as an optical signal source implementing a photonic signal millimeter and Terahertz wave generation scheme. As this requires a semiconductor laser, most of the solutions correspond to PICs based on InP material system.

Optical heterodyne sources most common approach has been to integrate two lasers on the same substrate and combine their outputs, following the same scheme used with discrete lasers. The key component for this approach is the integrated tunable semiconductor laser, on which effort has been invested for their interest in Wavelength Division Multiplexed optical networks [57], which can be implemented either through a Distributed Feedback (DFB) or Distributed Bragg Reflector (DBR) lasers. The advantage of photonic integrations is that it allows a wide range of component arrangements.

One reported solution has been to place the two lasers in axial configuration, including an optical phase modulator which is monolithically sandwiched between two DFB lasers. While this extremely compact solution features a continuous tuning range of more than 1 THz, the fact that the lasers have to pass each other to combine the two wavelengths limits the minimum spacing (and consequently, the lower frequency that can be generated). The minimum separation is determined by the stop bandwidth of the grating [58]. However, the bidirectional operation allows on-chip THz phase control via the optical phase modulator.

A more standard approach, shown in Fig. 10, is to integrate the two lasers next to each other, using monolithic passive optical components to combine the two wavelengths. The monolithic integration of two DFB lasers and an optical combiner has been a common solution, either with a Y-junction [59], [60] or MMI coupler. An important detail of such integrated schemes is that a reduction in the
free-running beat-note linewidth can be achieved increasing the length of the lasers [61]. It has been demonstrated that devices with 2500 μm cavity length exhibit a minimum full-width half maximum (FWHM) linewidth of less than 300 kHz, which was sufficient to establish a 1 Gbit/s ASK data transmission wireless link with the two wavelengths in a free-running state generating a 146-GHz carrier wave [14]. In these structures, the injection current produces a wavelength shift which is often used to tune the generated frequency.

This however creates an asymmetry in the optical power of each mode that increases as the required wavelength difference increases, as both wavelengths shift in the same direction.

A recent alternative that has been demonstrated makes use of a multi-wavelength laser structure based on an AWG laser which can be fabricated on a generic integration platform [62]. The device structure, shown in Fig. 11 (a) is an extended cavity laser, while Fig. 11 (b) shows a realization within a generic foundry. An array of semiconductor optical amplifier (SOA) is multiplexed into a single waveguide through the AWG. The AWG acts as an intra-cavity filter, to establish the lasing wavelengths filtering the modes in the laser cavity formed between the cleaved facets at the end of the channel waveguide on one side and the common waveguide on the other. The AWG selects a different wavelength for each AWG channel, and combines them on the common waveguide. The wavelength spacing among adjacent channels is determined by the AWG channel spacing, Δλ, typically around 0.8 nm (100 GHz). While the drawback of this approach is that it is difficult to tune the generated wavelengths, these are extremely narrow producing highly stable frequencies [63].

Regarding pulse sources, there have been two main approaches to integrate mode-locked (ML) semiconductor lasers on a single chip. The first one has been to use ring resonators, providing lithographic control of the cavity length [64]. The main drawback is that ring structures support two counter-propagating modes that compete for the gain, producing instabilities. This requires special design features such as s-shape structures to suppress one propagation direction [65]. The second approach uses a cleaved facet on one end of the cavity and a surface-etched grating on the other, with simpler fabrication process than a DBR [66].

Two new types of mirrors, shown in Fig. 12, avoid the need to use the cleaved facets at the chip edge, enabling on-chip cavity resonators. One option, shown in Fig. 12 (a), is to use Sagnac Loop Reflectors (SLRs). This solution employs an MMI coupler in which two of its outputs are connected to each other with a loop waveguide [67]. An alternative approach, shown in Fig. 12 (b) employs multi-mode interference reflectors (MIRs). These are an
alternative version in which the MMI is modified to provide an on-chip compact mirror structure that employs total internal reflection from a deep etch facet [68].

Using this type of mirrors it is possible to build an on-chip PML semiconductor laser. The extremely important advantage of this approach is that we gain lithographic control the cavity length, which in turn determines the repetition rate frequency, eliminating the uncertainty in the cavity length introduced by the facet cleaving process. In addition, we also achieve full control on the positioning of the SA section within the cavity. Moving the SA away from the mirrors, we achieve multiplying the repetition rate frequency by increasing the number of pulses in the cavity. In the top and bottom devices shown in Fig. 13, the SA was located at the center of the resonator. This allows the cavity to support two counter-propagating pulses that meet at the SA, reducing the energy required per pulse to saturate the absorber. The structure thus is known as colliding pulse mode-locked (CPM), and the repetition rate multiplies by the number of pulses. In the devices shown in Fig. 13, the top one, with cavity length $L_{\text{cav}} = 2210 \, \mu m$, aimed to a fundamental repetition rate of 18 GHz. As the SA is located at the center, the repetition rate doubles, achieving 36 GHz. This demonstrated the colliding behavior at a frequency within the range of our Electrical Spectrum Analyzer. The device at the center was a standard Fabry-Perot laser for comparison, with the same length as the device at the bottom, which was designed to reach the millimeter wave range, employing a shorter cavity, $L_{\text{cav}} = 1234 \, \mu m$. This sets a fundamental mode spacing of 34 GHz, while the colliding structure allows generating a repetition rate of 69.76 GHz. This is shown in Fig. 14, both on the optical mode spacing as measured using an Optical Spectrum Analyzer, as well as the electrical signal generated coupling the optical output from the laser to a photodiode (U2T XPDV4120R) with 90-GHz (3-dB) bandwidth, connected to an external mixer to downconvert the signal. Locating the SA asymmetrically in the resonator is expected to increase the repetition rate into the THz range.

4.3 Integrated Transmitters

Within the previous section, we describe different semiconductor laser structures, which can be integrated on a PIC, that implement a photonic-based millimeter- or terahertz wave signal generation source. However, dedicated fabrication platforms allow a significant increase in the functionality offered in a single chip.

A demonstration that has established the state-of-the-art was achieved within the iPHOS (integrated Photonic Signal Sources) project, funded by the European Commission. The level of integration was raised to the point of achieving a full millimeter-wave wireless transmitter in a single-chip, shown in Fig. 15 (a). As shown in the block diagram in Fig. 15 (b), the chip includes two single mode DFB lasers
combined through an MMI on both extremes of the DFB lasers. The left hand side coupler takes the optical signal to the chip edge, providing an optical output of the dual wavelength signal. On the right hand side of the DFBs there is an integrated optical waveguide to a monolithic high-speed photodiodes (PD) at which the millimeter electrical signal is generated. The dual mode optical signal passes through an electro-absorption modulators (EA) for data modulation and an SOA to boost the optical power within the waveguide. Further details on the structure have been reported previously [69].

With such structure, we have achieved a wide continuous tuning range of the wavelength spacing, over 20 GHz, on different frequency ranges that depend on the initial grating difference. For the device reported, Fig. 16 (a) shows the change in the optical spectrum as the bias current on DFB1 is fixed at 75 mA while the current on DFB2 is varied between 90 mA to 40 mA. When the currents on the two lasers are close to each other (70 mA), the generated beat signal is given by the offset among the grating on each device. As the currents are varied, we can tune the generated frequency. Increasing the current shifts the wavelength towards longer wavelengths, which as shown in Fig. 16 (a) is used to reduce the spacing, while a decrease in the current shifts the wavelength in the opposite direction. This is an indication that the nature of the tuning is due to temperature in the active layer, with some thermal crosstalk among the two emitters. The fact that the two wavelengths are shifted when only one bias current is changed indicated that some thermal crosstalk exists between the two. An important associated effect of this tuning method is that it also affects the amplitude difference of the modes. This is the main reason for having individual SOAs before the two wavelengths are combined on the MMI coupler. Unfortunately in the tested samples the contact pads of SOA1.1 and SOA2.1 were shorted and we could not compensate for the current level difference on the DFBs. The beat note that is generated on the integrated photodiode, biased at −2.5 V, for each of the different optical spectrums shown previously, is presented in Fig. 16 (b). For the measurement we used an F-band sub-harmonic mixer, with a LO frequency of 45 GHz, thus the x-axis represents an offset frequency to which must be added 2 x 45 GHz = 90 GHz. The tuning range achieved goes from 92 GHz to 110 GHz.

One of the main drawbacks which we have mentioned for optical heterodyne sources that use two different emitters is that the wavelengths are not correlated, and therefore have an excess phase noise. Integrated sources based on DFB lasers have been demonstrated in wireless links at low data rates (100 Mb/s) without any locking scheme [69]. However, in order to reach higher data rates, some phase locking technique must be used. One important advantage of DFB laser structures that include a wavelength selective optical filtering structure within the active region of each emitter is a phase locking when an external optical frequency comb is injected directly into both emitters. Optical injection locking the integrated lasers produces high-spectral-purity signals at frequencies >100 GHz, with phase noise spectral density below −90 dBc/Hz at offsets from the carrier greater than 10 kHz [70]. This is sufficiently stable to achieve a bit-error rate below 10−11 in a 10-Gbit/s coherent wireless transmission link in the W-band (97 GHz carrier frequency) without active phase stabilization on the transmitter side and digital signal processing [71].

5. Conclusion

In this paper, we have reviewed recent progress in THz communications technologies enabled by photonics. Photonic generation of high-frequency carrier wave carriers provides an efficient access to the millimeter and terahertz frequency ranges for ultrahigh data-rate wireless communications.

At carrier frequencies from 100 GHz to 200 GHz, electronics-based systems with Si-CMOS as well as III-V semiconductor devices have started playing a key role in place of photonics-based ones. 200-GHz and 300-GHz bands have currently been major research targets to achieve 50-Gbit/s to 100-Gbit/s data rate with both approaches. We have described a real-time 300-GHz band wireless link at 50-Gbit/s data rate with photonics-based systems as a technology demonstrator. In addition, photonics facilitates the convergence of the wired (optical fiber) and wireless communications.
Recent efforts have demonstrated the implementation of millimeter-wave sources using photonic integrated circuits. Monolithic approaches on InP are very much advanced, integrating all the necessary elements on a single chip. The major drawbacks that we have observed are the highly complex fabrication process flow (three epitaxial regrowth steps), the limited tuning range (around tenths of GHz) and the number of compromises that must be made to monolithically integrate all the components, which limit the performance of photodiodes, and SOAs. In our view, an optimized photonic-electronic convergence will require hybrid integration approaches, using standardized components as well as assembly and packing solutions.

The photonic integration approach is now at an extremely exciting stage, in which there are multiple options competing among each other. Generic foundry technology platforms will play an important role in providing the low-cost development of the photonics-based THz transceivers. It will provide tunability/bandwidth of 100 GHz to 1 THz and a data rate of over 100 Gbit/s, which will not be easily achieved by all electronic approaches.

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