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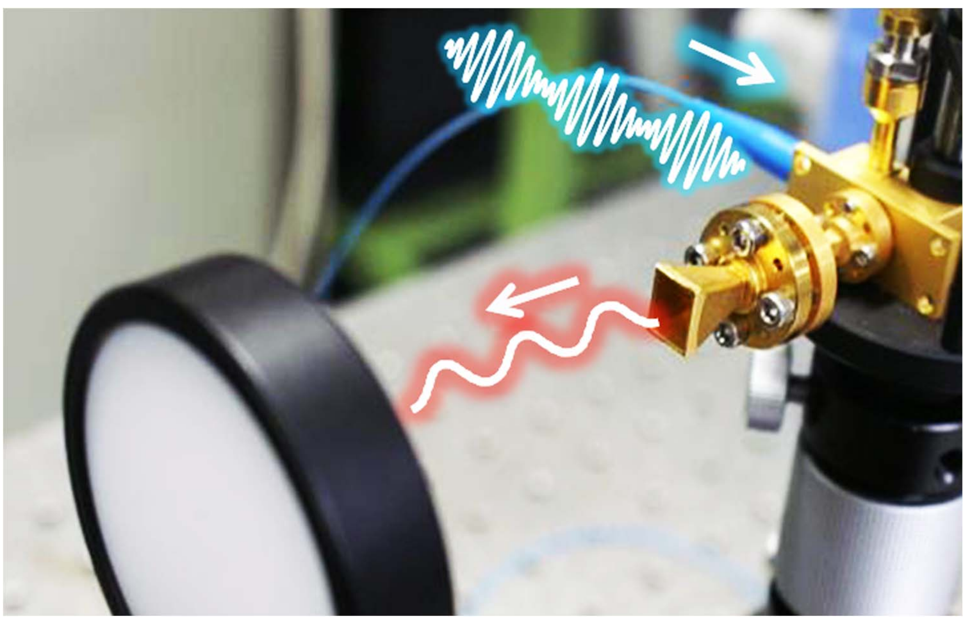

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Breakthroughs in Photonics 2013: THz Communications Based on Photonics

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Abstract: There has been an increasing interest in the application of terahertz (THz) waves to broadband wireless communications. In particular, use of frequencies above 275 GHz is one of the big concerns among radio scientists and engineers, because these frequency bands have not yet been allocated at specific active services, and there is a possibility to employ extremely large bandwidths for ultrabroadband wireless communications. Introduction of photonics technologies for signal generation, modulation, and detection is effective not only to enhance the bandwidth and/or the data rate but also to combine fiber-optic and wireless networks. This paper reviews recent progress in THz wireless communications using telecom-based photonics technologies towards 100 Gb/s.

Index Terms: Wireless communication, photonics, photodiode, millimeter wave, terahertz.

1. Introduction

On January 30, 2014, the Ministry of Internal Affairs and Communications (MIC) of Japan officially revised the radio regulations to allocate the band from 116 GHz to 134 GHz for the 120-GHz band wireless link for broadcasting services. This is the first industrial allocations of over-100-GHz carrier frequencies, a beginning frequency edge of terahertz waves defined as electromagnetic waves from 100 GHz (0.1 THz) to 10 THz. It has passed 14 years since a born of the 120-GHz band wireless link in 2000 [1]. At that time, 120-GHz band signals were generated and modulated by means of photonics technologies, since electronic components such as oscillators and modulators with sufficient bandwidth were not available. Its unprecedented data rate of 10 Gb/s attracted the broadcasters who had a need to transmit multiple channels of high-definition (HD) TV data over the distance of 1 km [2]. In 2004, the MIC approved the photonics-based transmitter as an experimental radio station which was introduced to examine the usefulness and practicality of the link in the outdoor. The photonics-based 120-GHz wireless technology also activated a development of electronic devices and integrated circuits such as amplifier MMICs to strengthen the wireless technology, and finally all electronic MMIC-based systems were successfully developed and deployed in real-world events such as the 2008 Beijing Olympic Games [3].

Now, the demand for much higher speed wireless technology is ever increasing in accordance with a rapid advancement of mobile networks and rich contents handled by the networks. The prospective data rate for wireless communications in the marketplace will be 100 Gb/s within ten years. Against this background, researchers have recently been seeking the use of radio waves

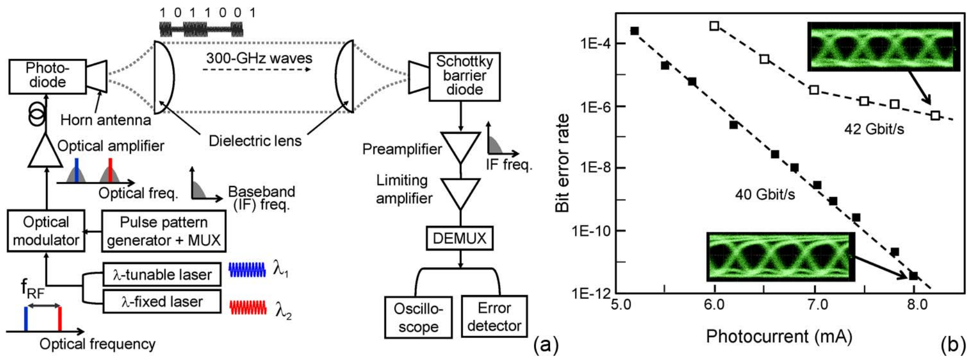

Fig. 1. (a) Schematic diagram of experimental setup to evaluate transmission characteristics of 300-GHz wireless link based on ASK modulation and direct detection. (b) Bit error rate (BER) characteristics at 40 Gb/s and 42 Gb/s and corresponding demodulated eye diagrams at 40 Gb/s. Photocurrent [horizontal axis of (b)] is proportional to the square root of the transmitted power.

whose frequency is over 275 GHz for ultrahigh-speed wireless links, since the frequency bands from 275 GHz to 3000 GHz are not yet allocated for specific active services in the world, and there is a possibility to employ extremely large bandwidths for ultra-broadband wireless communications [4]–[9]. Even though existing microwave and millimeter-wave wireless technologies will enhance their data rates by improving the spectral efficiency with use of multi-value modulation schemes such as 16 QAM or MIMO (multiple input multiple output) techniques, the THz communications will promise a data rate of 100 Gb/s using relatively simple modulation schemes like ASK and QPSK because of their broad bandwidths.

As we have experienced in the development of 120-GHz band system, introduction of photonics technologies for signal generation, modulation and detection is very effective not only to enhance the bandwidth and/or the data rate, but also to fuse wireless networks into fiber-optic (wired) systems. In addition, photonics-based approach is expected to bring such ultra-high data rate wireless technologies to potential users and to meet and explore real-world applications at the earliest opportunity as a technology driver [8]. For this purpose, demonstration of “real-time” wireless transmission is required without use of an “off-line” digital signal processing [10], [11]. In this paper, we present a recent progress in real-time error-free wireless transmission technologies using THz waves towards 100 Gb/s and more.

2. Photodiode Technologies

In the photonically-assisted THz signal generation, the O/E converter ultimately determines the transmitter performance with respect to the bandwidth and output power. Among various types of O/E converters, a high-frequency photodiode called a uni-traveling-carrier photodiode (UTC-PD) has been most commonly used [12], [13]. The performance of the UTC-PD has been improved in terms of band structure, device structure, circuit design, and thermal management since its debut in 1997. The diode chips are usually packaged with hollow waveguide structures, or monolithically integrated with planar antennas such as bow-tie and dipole antennas. Array of photodiodes promise an increase in the output power; over 1-mW output power has been achieved from two photodiodes [14]. Most recently, integration of photodiodes with lasers and modulators has been proposed and demonstrated as a photonic Integrated circuit (PIC) [15]. The PIC will make the photonically-assisted approach much competitive with all electronic approach with respect to cost and size, while maintaining the superior performance.

3. ASK Modulation and Direct Detection Systems

Fig. 1 shows a block diagram of the experimental set up to evaluate the wireless link based on intensity modulation and direct detection scheme [9]. For the modulation, we used an electro-optic intensity modulator (EOM) driven by electrical data signals from a pulse-pattern-generator up to

50 Gb/s. The modulated optical signal is amplified by an Er-doped fiber amplifier (EDFA). An optical filter is inserted to eliminate the amplified spontaneous emission noise from the EDFA. Finally, the optical signals are input to the waveguide-mounted UTC-PD to generate THz waves at 300 GHz, setting the wavelength difference of the two lasers to 2.4 nm. THz waves are radiated from the horn antenna, and dielectric lenses are used to collimate and focus THz waves for the transmitter and receiver, respectively. The total antenna gain is about 40 dBi. The distance between the transmitter and receiver is 0.5 $\sim$ 1 m, where there is little change in the received power and a multi-path effect is small.

The data signal is demodulated by a Schottky-barrier diode (SBD) detector which is mounted on WR-2.8 waveguide structure and has a 3-dB IF (baseband) bandwidth and 6-dB bandwidth of 19 GHz and 28 GHz, respectively, at a zero-bias voltage. 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 μW. The output IF signal is amplified by a 38-GHz pre-amplifier and reshaped by a 35-GHz trans-impedance amplifier used as a limiting amplifier.

The performance limitation with respect to the data rate is determined mainly by the bandwidth of the UTC-PD in the transmitter and that of the SBD detector in the receiver. The 3-dB RF bandwidth of the UTC-PD is 140 GHz (from 270 to 410 GHz), while the RF bandwidth of the SBD detector also exceeds 100 GHz. Thus, the IF bandwidth of the receiver currently limits the maximum bit rates. Fig. 1(b) shows eye diagrams demodulated by the receiver and the bit error rate (BER) characteristics at 40 Gb/s and 42 Gb/s [6]. Error-free $(\mathrm{BER} < 10^{-11})$ transmission has been achieved at 40 Gb/s, which is the highest data rate ever reported for "error-free" wireless links without forward error correction (FEC). When the data rate is 42 Gb/s, a floor has been observed in the BER characteristics, which is caused by the limitation in IF (baseband) bandwidth of SBD detector. In Fig. 1(b), 8-mA photocurrent of the UTC-PD corresponds to the transmitter output power of 90 μW.

Use of plasma-wave field-effect transistor (FET) detectors in place to SBD detectors has also been examined [16], [17] for the THz communications application. The operation frequency limit of the plasma-wave detector is determined not by the cut-off frequency of the transistor, but by the nonlinear properties of the 2D plasma in the transistor channel. It has been confirmed that THz signals at frequencies from 250 GHz to 340 GHz can be detected with a 18-GHz transistor commercially available, and the wireless communication has been successfully demonstrated by using the plasma-wave detector [17]. Moreover, sensitivity of the plasma-wave detector is potentially much higher than that of the SBD [18].

Polarization multiplexing is a practical way to increase the bit rate. For polarization multiplex (MUX) and de-multiplex (DEMUX), we used ultra-broadband wire-grid polarizers. With use of two pairs of photonics-based ASK transmitters and direct detection receivers, an error-free 300-GHz band link at 24 Gb/s for each channel has been demonstrated, which corresponds to the total throughput of 48 Gb/s [19]. Thus, the maximum data rate obtained by the SISO link can be easily doubled, for instance, from single channel 40-Gb/s data rate to the total throughput of 80 Gb/s.

Much larger bandwidth can be ensured when the carrier frequency can be shifted higher. By using the antenna-integrated UTC-PD module together with the 600-GHz band SBD detector (WR-1.5 waveguide), we have increased the available bandwidth of more than 250 GHz with a single transmitter/receiver pair [9]. Error-free 1.6-Gb/s transmission has been demonstrated at carrier frequencies from 450 GHz to 720 GHz. Such a huge available bandwidth corresponds to more than 100-channel transmission of uncompressed high-definition (HD) TV signals.

4. Coherent Systems

The next step to further enhancing not only the data rate of over 100 Gb/s but the link distance as well is to introduce a multi-level modulation such as QPSK using coherent THz carrier signals and a coherent modulation/demodulation scheme using a harmonic mixer, for example, [20]–[23]. For a real-time transmission experiment, frequency- and phase-stabilized THz signal generation scheme in the transmitter is required, in contrast to the use of free-running lasers shown in Fig. 1. To stabilize the frequency and phase of THz carriers, we used an optical frequency comb-generator followed by an arrayed waveguide grating (AWG) optical filter and optical phase stabilizers [24]–[26].

As a proof-of-concept experiment, we conducted a coherent transmission experiment with carrier frequencies of 100 GHz [25] and 200 GHz [26] and ASK modulation up to the bit rate of 12.5 Gb/s. In addition, a required output power of the transmitter for the error-free transmission is more than one orders of magnitude smaller comparing to the case of direct detection.

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