Wireless Data Transmission Method Using Pulsed THz Sliced Spectral Supercontinuum

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***Abstract*— A method of ultrafast wireless information transmission using spectrum-sliced supercontinuum (SC) along the THz frequency range is presented in this letter. The THz spectrum-sliced SC was formed by femtosecond optical pulses doubled in a Michelson interferometer before being input onto a MgO:LiNbO$_3$-THz generator. Two THz pulses generated by femtosecond pulses within a MgO:LiNbO$_3$-crystal provided the spectrum-sliced SC in the spectral domain, which was recorded by an electro-optical detection system. The transmission rate in this method is determined by the bandwidth of the THz spectrum, the number of spectral lines in the SC, and the pulse repetition rate. We have demonstrated an SC containing 31 spectral lines with 23-GHz spacing within the range from 0.04 to 0.75 THz. The signal with encoded information was successfully transmitted over 2.4 m in free-space.**

***Index Terms*— Submillimeter wave communication, terahertz, time-domain spectroscopy, wireless communication.**

I. Introduction

BASED on Edholm's law, [1] in 2004, one could expect that data transfer speeds in modern networks would reach hundreds of Gbit/s by 2020. However, current optical network systems allow such data rates. Moreover, experimental research systems have been shown to surpass these metrics—in previous work, a 110-channel, 10.7 Gbit/s Dense Wavelength Division Multiplexing (DWDM) signal was transmitted for 1040 and 2000 km with Q-factors of more than 15.6 and 11.4 dB respectively [2]. Carrier-suppressed return-to-zero format has also been transmitted over 80 km with speeds up to 3.24 Tbit/s [3]. Furthermore, data transfer speeds in modern optical fiber networks achieve Petabit/sec (Pbit/s) levels [4]. The performance of wireless networks must meet higher requirements as well. The most feasible approach to achieve 100 Gbit/s and higher speeds in wireless networks involves a transition from gigahertz to terahertz frequency range (0.1 to 10 THz), thereby increasing the frequency band by 2-3 orders [5], [6]. An advantage of THz wireless networks is the possibility of creating a secure communication system. It is not obvious but quite probably in the near future [7], [8]. THz communication systems are developing actively now. The first proof-of-concept devices such as broadband THz communication systems based on uni-traveling-carrier photodiodes with the potential data-rate of 640 Gbit/s [9] and 300-GHz-band wireless communication systems with real-time error-free transmissions at 50 Gbit/s have been developed in [10]. Further, spectrum broadening is very promising for increases in data transfer rates. In the case of broadband THz radiation it is promising to apply helical beam advantages wireless communication systems [11], [12].

THz wireless communication systems are divided into optical, electronic and hybrid (mixed), depending on the components used. Hybrid systems are most commonly used because it is the combination of electronic and optical devices that allows to obtain the highest speed [13].

Data transmission in existing THz wireless communication systems and prototypes is implemented usually in one spectral channel with quadrature amplitude/phase modulation. For example, in [14] a speed of 3Gbit/s was reached with quadrature amplitude/phase modulation. It is possible to create effective and fast THz amplitude modulators based on high electron mobility transistors and metamaterials that can work with 1 GHz modulation speeds and with 85% modulation depth on selected frequencies [15]. Another promising method of THz radiation modulation in communication systems is the use of photo-induced Fresnel zone plates and diffractive optical elements [16]. With such techniques, it is possible to steer THz beams with different frequencies in Wavelength Division Multiplexing (WDM) systems.

Time-domain THz systems have spectral bandwidths of tens or hundreds of THz, which is much more promising for communication in comparison to electronic systems. However, this direction is not developed well at present. Data transfer with simple on-off modulation of THz pulses is demonstrated in [17] and [18]. Usage of 100 GHz non-interfering channels sliced in THz pulse spectrum can provide higher data rates in comparison with current state-of-the-art [19]. Methods for THz multiplexing and demultiplexing are developing now [20], [21]. This makes broadband THz spectrum channel formation a very important task. Alfano and

Manuscript received August 9, 2017; revised September 8, 2017; accepted November 16, 2017. Date of publication November 23, 2017; date of current version December 19, 2017. This work was supported by the Government of Russian Federation, through the Project 3.9041.2017/7.8, under Grant 074-U01. *(Corresponding author: Yaroslav V. Grachev.)*

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Digital Object Identifier 10.1109/LPT.2017.2777338

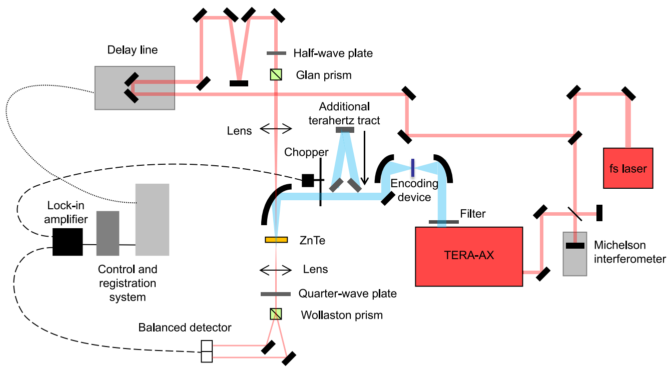


Fig. 1. The schematic of the experimental setup for wireless data transfer demonstration in THz spectrum-sliced supercontinuum.

Shapiro observed self-phase modulation in picosecond optical pulses which provide broadband spectrum radiation [22] and explain this process via four-wave mixing mechanism [23]. In the optical range, a large number of channels can be created using spectrum-sliced supercontinuum (SC) by arranging the interference of the two pulses with ultra-broadband spectra [24], [25]. Alfano and Zeylikovich [24] proposed to use each of the many spectrum-sliced SC spectral lines as a single information transfer channel in systems employing wavelength division multiplexing. Another possibility of data transfer is using 250 nm bandwidth spectrum-sliced SC demonstrated in [25]. In their paper, each spectral line is considered to carry one bit of information; therefore, the entire SC can be treated as a word. The transmission speed is determined by the spectrum bandwidth of the pulses, the amount of spectral lines in the SC, and the pulse repetition rate. The use of "white-light continuum" sources provide wide opportunities in telecom applications [26]. A similar approach can be used for transmission of a data in the THz frequency range where the most developed and powerful sources are the broadband sources based on femtosecond laser systems. The generated pulse in this case is a spectral SC occupying bandwidth from 0.1 up to 10 THz in some cases [27].

This letter demonstrates the principle of a wireless information transmission method using spectrum-sliced SC in the THz frequency range created by a titanium-sapphire femtosecond laser, a Michelson interferometer, and a $MgO:LiNbO_3$ THz generator.

II. Experimental Setup

The experimental scheme of wireless information transfer in the structure of a THz spectrum-sliced SC consists of the following functional elements (Fig. 1): a femtosecond laser source, a Michelson interferometer to create two optical pulses, a terahertz radiation generator (TERA-AX), the encoding information unit (Encoding device), free-space channel for data transmission, the detection system of THz pulses (electro-optical sampling detector consisting of ZnTe crystal, quarter-wave plate, Wollaston prism, and optical balanced detector), and the delay line. The additional terahertz tract formed by three mirrors make THz path longer up to 2.4 m. We detect and compare THz signal on distance 0.4 m and 2.4 m

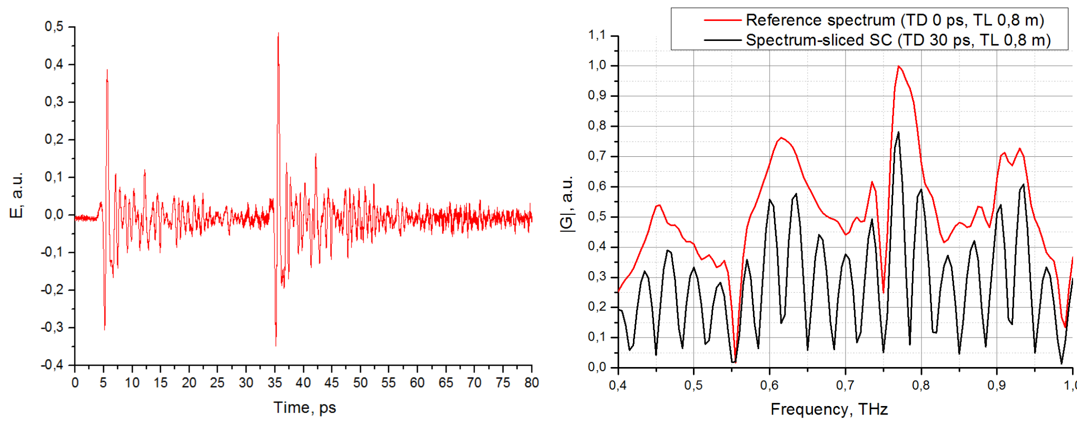
A mode-locked Ti:sapphire amplifier (Regulus 35F1K, Avesta Ltd.) is the optical source. It generates laser pulses with a central wavelength of 800 nm, pulse duration less than 35 fs, and pulse energy of 1 mJ at repetition rate of 1 kHz [28]. Laser pulses were doubled in the Michelson interferometer with an adjustable time delay between the pulses (Fig. 2a). A pair of femtosecond pulses were directed onto the generator of THz radiation TERA-AX (Avesta Ltd.) [29], which uses an optical rectification of femtosecond radiation with tilted wave front in the $MgO:LiNbO_3$ crystal. The terahertz radiation average power was 400 μW. Two femtosecond pulses generate two terahertz pulses and create a spectrum-sliced SC which was recorded by electro-optical detection system [30]. The bandwidth of THz radiation covers the range from 0.1 to 2 THz. One of the atmosphere loss minima is located in the range between 0.4 to 1.0 THz [7], [13], [31]; therefore, we chose exactly this part of the spectrum for the data transfer experiment (Fig. 2b).

III. Experimental Results and Discussion

We have used a 1 mm thick high-resistivity silicon wafer to realize N-bit encoding of information in the formed THz spectrum-sliced SC. It works as a spectral Fabry-Perot filter and modulates the amplitude of individual spectral lines. Of course, such methods need to be replaced by real-time spectrum-resolved data encoders for use in ultrafast telecommunication systems. It is possible to replace this static modulation up to dynamic by method reconfigurable photo-induced Fresnel-zone-plate [16] or by use of a leaky-wave antenna to demultiplex the channels [20] and encode information via phase modulation devices [32]. It is acceptable to spread broadband THz spectra by gratings with suitable period for multiplexing and demultiplexing as well as in optical range [25]. Obviously, the highest modulation rate will be achieved by ultrafast optics. Extremely large refractive index nonlinearity of some crystals in the terahertz spectral range was predicted in [33]. Thus, we expect the creation of ultrafast light control systems in the terahertz spectral range based on such crystals.

We use simple static modulation of the THz spectrum to show data transfer opportunities utilizing channels formed by spectrum-sliced SC in broadband THz radiation. The data rate depends on the methods of modulation which will be applied in future systems. Further, we experimentally defined that the Fabry-Perot modes of the 1 mm silicon wafer have two times lower period compared to the period of spectrum-sliced SC formed by two THz pulses with 43.2 ps time delay between them (Fig.3 blue curve). A periodic 31-bit spectral signal with binary code formed after the modulator (see Fig. 3 red curve).

Terahertz radiation with encoded information in 31 spectrum-sliced SC lines has been propagated in free-space (room temperature – 21°C, humidity – 40%) with the aid of parabolic and flat mirrors and has been measured at distances of 0.4 and 2.4 m from the source. All measurements were averaged 23 times. The use of an ordinary delay line based on stepper motor translation stage takes long time to achieve one working signal with



a b

Fig. 2. A temporary form (a) and (b) sliced supercontinuum spectrum of terahertz pulse pair. TD – time delay between femtosecond pulses in Michelson interferometer; TL – distance from THz generator to the detector.

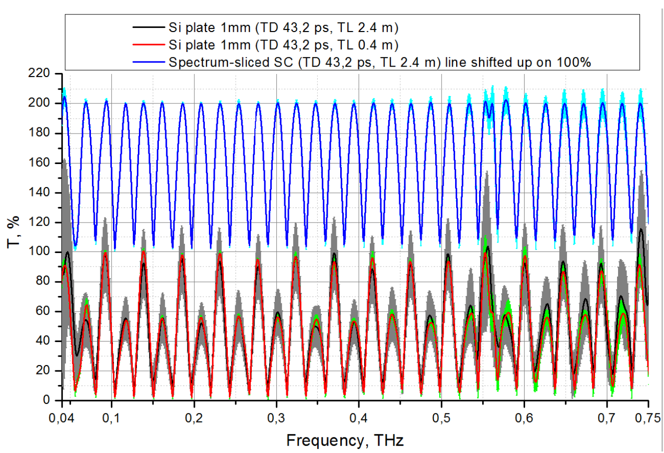


Fig. 3. THz spectrum-sliced supercontinuum used for data transfer. 31 lines prepared for data coding (blue line, cyan error-bars) and the information signal after passing 0.4 (red line, green error-bars) and 2.4 m (black line, gray error-bars) distances in free-space. TD – time delay between femtosecond pulses in Michelson interferometer; TL – distance from THz generator to the detector.

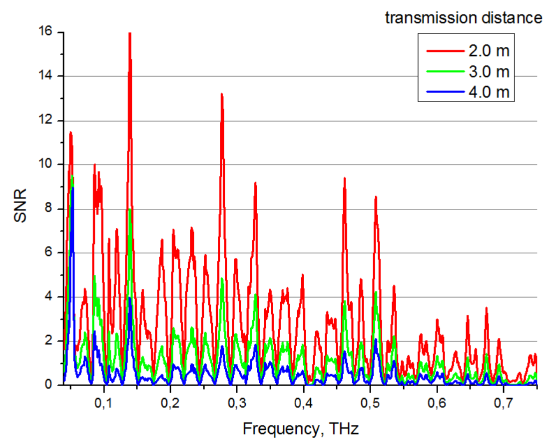


Fig. 4. SNR for different THz signal transmission distances.

acceptable SNR - 138 minutes for 23 measurements. Single-shot measurement or fast rotary delay scan allow reduce measurement time down to 0.4 – 1 second level [34], [35]. Comparison of the coded spectrum-sliced SC structure signals registered at the distances of 0.40 and 2.40 m (Fig.3) showed full frequency, width, and amplitude match of spectral peaks. Amplitude errors in carrier spectrum in the 0.04–0.75 THz range were between 3–20% (Fig.3 blue curve, cyan error-bars). Information encoding raised measurement errors to 10–20% for a signal registered at 0.4 m after THz source and 25–45% for the signal registered after 2.4 m propagation in free-space after the THz source (Fig.3 red and black curves, respectively). The error was recorded to be 75% at frequencies corresponding to water vapor absorption lines, but differences between signals were lower than 5–20%. We calculated losses and the signal-to-noise ratio (SNR) from signals measured at different distances and extrapolated SNR for all channels for the 2.0, 3.0, 4.0 m distances. For the 2.0 m distance SNR values for some channels fall below 2 and below 1-0.5 for 3.0 m (Fig. 4). This means that for the longer distances, it is necessary to raise SNR by averaging. It suggests that the structure of the broadband spectrum has been preserved, in contrast to the process of the dispersion broadening of ultra-short waveforms, quadrature amplitude/phase modulation, and binary amplitude modulation during propagation in the atmosphere [31]. Even water vapor absorption lines did not influence the signal transmission beyond a measurement error in this experiment. In commercial communication systems, it is essential to form spectrum-sliced SC channels at the atmospheric transparency windows [36].

The normalized amplitude of the individual spectral peaks has changed to 20-60% due to water vapor absorption. However, this absorption is included in measurement error and can be considered by applying appropriate spectral filters during the data processing stage.

IV. Conclusion

A technique of communication channel formation for wireless information transmission by spectrum-sliced SC in the THz frequency range is suggested in this letter. The information bits are contained in the structure of spectrum-sliced SC. The data rate is determined by the amount of spectral lines in the spectrum-sliced SC, the modulation frequency which didn't exceed laser pulse repetition rate. We transfer 31 bits encoded in broadband spectrum of THz pulse. Using 31 spectral lines with a repetition rate of 1 kHz provides a data transfer rate of 34.1 Gbit/s. The increase of a data rate is possible due to the increase of number of spectral channels, as well as the clock frequency (repetition rate) of the THz pulses. In particular, modern femtosecond laser systems demonstrated the generation of pulses with a repetition rate up to 100 GHz [37], that can, in principle, increase a data rate up to 3 Tbit/s for the future wireless communications. Measuring signal by time-domain technique is a bottleneck for communication applications. It drops data rate so dramatically, that such systems are not applicable in communications yet.

An effective and frequency-tunable modulating device for THz signal with a frequency range of about 0.1-10 THz is not yet available. However, for an efficient data transfer by our method, any amplitude or phase THz spectral modulator is acceptable. Combinations of channel forming techniques—such as the one performed in this article—with channel demultiplexing and multiplexing methods in [20], and modulation techniques in [32] can create high data rate communication systems using broadband THz radiation.

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