Photonics based frequency hopping spread spectrum system for secure terahertz communications

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Abstract: Terahertz (THz) spectrum (100 GHz-10 THz) is considered the next frontier in the design of high-speed wireless communication systems. While the high-power THz sources have commercially become available, it increases the possibility of developing THz jammers to disrupt the THz communication link. Therefore, the development of novel anti-jamming solutions is the need of the hour. In this work, we present the photonics-based THz communication system and demonstrate the frequency hopping spread spectrum (FHSS) technique which acts against the single/multi-tone jamming attack in the frequency window of 110 GHz-170 GHz. By tuning the output wavelength of the distributed feedback lasers, the THz carrier frequencies are swept back and forth within the scanning window. The frequency tuning range was measured for different scanning rates of the laser which decreases rapidly with the increase in the scanning rate. Next, we demonstrate the THz FHSS technique in a real-time communication system by transmitting a 6 Gbps NRZ signal in both wireless and THz-fiber-based links within the link distance of 1.75 m. We experimentally found that the measured bit error rate in the THz FHSS system is the time average of the measured BER for individual carrier frequencies within the hopping frequency window. By combining with the forward error correction codes and by using the tunable filter in the receiver, we believe that the proposed technique will offer a novel and compact solution against the single/multi-tone jammer for high-bit rate THz communications.

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1. Introduction

Due to ever-increasing data traffic, the terahertz (THz) spectral band (100 GHz-10 THz) is considered the next frontier in high-speed wireless communications [1–6]. Particularly, as the 5G communication systems have become a reality in several countries and are expected to offer the peak data rate of ~20 Gbps, the beyond 5G/6G communication systems (carrier frequency of >100 GHz) will be expanded to provide the bit rates of 10-100 times higher than 5G systems [7–9]. In the past years, several research works have been carried out that demonstrate the transmission of high bit rate data (>100 Gbps) at carrier frequencies of >100 GHz and over a wireless link distance of a few centimeters to several meters [10–13]. In this vicinity, one of the important factors that need to be addressed in designing the next-generation communication links is the security against eavesdropping or jamming [14–16]. It is widely assumed that the communication link with a narrow transmission beam (i.e., THz waves with a lower angular divergence) is more challenging for the eavesdropper to detect and read the data. However, a recent study shows that by placing an object in the transmission path, the highly directional THz beam undergoes scattering in a different direction and favors the eavesdropper [17]. There are few works in the literature, that present the solutions such as multipath propagation, quantum key distribution, optimized intelligent reflective surface, etc., to mitigate the effects of eavesdropping [18–20]. Another commonly used method in telecommunications for establishing a secure communication link is the spread spectrum technique [21–23]. The spread spectrum refers to the deliberate
spreading of the data signal to a wider bandwidth (i.e. more than the required bandwidth for the data signal) in the frequency domain. This approach results in minimizing the effect of signal interference, fading, and establishing a secure and reliable communication link against jamming or eavesdropping [24]. Two major spread spectrum techniques are widely used in modern communication systems namely direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS) [24]. In DSSS, the narrowband data signal is directly mixed with the wide bandwidth spreading sequence in which the chip rate ‘$R_c$’ of the spreading sequence must be higher than the bit rate ‘$R_s$’ of the data signal i.e. $R_c >> R_s$ to achieve a wider spectrum in the output of the transmitter which resembles that the data is buried under the wide bandwidth noise spectrum and makes it difficult to intercept [21]. In the receiver section, the same spreading sequence must be used to despread the received signal and recover the data signal. Alternatively, the FHSS refers to the switching of the carrier frequency within a given bandwidth with respect to a certain hopping pattern. In other words, the carrier frequency varies as a function of time in a predetermined order within the given spectral range [21]. In the hopset of ‘$M$’ possible carrier frequencies ($f_1, f_2, f_3, f_4, ..., f_M$) with each hopping frequency of bandwidth ‘$B$’, the hop rate defines the rate at which the carrier frequency changes to the new frequency in the hopset [24]. In the receiver unit of the FHSS system, the same hopping pattern as the transmitter must be used to decode the information. Depending on the applications, both DSSS and FHSS techniques have their own advantages and challenges. For example, the DSSS system has a longer coverage range due to the requirement of a lower signal-to-noise ratio (SNR) whereas the FHSS system supports higher bandwidth and negligible near-far problem (Effect of the reception of strong signal coming from a nearby source which makes it hard to hear the weaker signal which is farther away) [21]. In terms of anti-jamming applications, the performance of both DSSS and FHSS is appreciable for single-tone jammers. Particularly, to mitigate the effect of a single-tone jammer (without noise modulation), the FHSS system can implement the forward-error-correction (FEC) code (Reed Solomon, Raptor, etc.) for the partially blocked frequency and recover the data [25–27]. The FEC scheme can be still implemented in the FHSS system against the multi-tone jammer that operates without any random noise modulation. Moreover, since the THz band possesses larger bandwidth with most of the intended applications in short-distance communications (shopping malls, universities, military base, etc.), utilizing the FHSS technique can be considered a highly advantageous solution against single/multi tone jamming. In THz communications, an alternative form of frequency hopping technique (distance-adaptive absorption frequency hopping) was proposed and demonstrated [28]. In this approach, the carrier selection scheme was designed to choose optimal hopping frequencies at molecular absorption peaks in the THz band and therefore the reliability of THz transmission and covertness from eavesdropping is guaranteed. Similarly, several hopping schemes were proposed in THz nano-sensor networks which are energy efficient and overcome the problem of dynamic molecular absorption in composition varying channels [29–31]. In general, the FHSS systems are designed using all electronics-based systems. Particularly, the transmitter comprises a digital frequency synthesizer whose output frequency can be randomly switched using a pseudo-noise (PN) sequence, which results in the generation of FHSS within the given bandwidth [32]. The frequency switching can be either slower (slow frequency hopping where more than 2 bits are transmitted at the same frequency) or faster (fast frequency hopping where 1 bit is transmitted by two or more frequencies). Thus, the electronics-based approach is advantageous, particularly for the fast switching of the carrier frequencies. However, it is difficult to achieve ultra-wide bandwidth coverage due to limited source tunability. This particular limitation is especially pronounced in the electronics-based THz communication system, where the carrier frequencies are generally generated using frequency multiplier chains and the tuning range is limited to a few tens of GHz.

On the other hand, frequency hopping in optical communications exists which in general uses the ‘$N$’ number of lasers for the generation of the ‘$N$’ different carriers [33]. Here, the data can be
fragmented into segments and mapped to different optical carriers using a field-programmable gate array (FPGA). Alternatively, it is possible to use an optical frequency shift keying (OFSK) transmitter which generates two tones by direct modulation of distributed feedback (DFB) lasers along with the electro-absorption modulation for the optical frequency hopping (OFH) generation [34,35]. This approach is still attractive for OFH generation; however, the modulation bit rate is limited by the response of the DFB laser and the number of carrier waves generated is low (2-4 in most cases) [35,36].

A similar photonics-based technique can be used for the generation of THz waves. In this approach, two DFBs operating with slightly different center wavelengths are mixed in a nonlinear device (photomixer) which then generates the frequency difference (THz spectral range) between the two laser wavelengths [37,38]. By tuning one or both lasers, it is possible to tune the THz frequency over a broad spectral range (>3 THz). Although we can achieve the ultra-wide bandwidth tuning, the proposed technique is generally slower and only a linear frequency hopping pattern can be achieved. However, it is still preferred to use the linear hopping pattern and slow scanning approach instead of having a fixed carrier frequency as seen in most commonly used THz communication systems. This approach is particularly suitable for anti-jamming applications in the THz spectrum when the frequency of the jamming signal is continuous i.e. without any random noise modulation (single tone or multi-tone jammers without modulation). In the following, we further detail the advantage of the photonics-based THz FHSS system in anti-jamming applications. In incoherent THz communications, the zero bias Schottky diodes (ZBD) with broad bandwidth are generally used as the envelope detector.

Let us assume that the bandwidth ‘B’ of the ZBD is large enough and that can detect the THz signal in the frequency range of $f_L$ (low frequency) to $f_H$ (high frequency) and demodulate the baseband signal. The THz transmitter (Alice) transmits the ON-OFF keying modulated signal with the carrier frequency of $f_T$ which is anywhere between $f_L$ to $f_H$. In this scenario, it is well known that the receiver (Bob) will fail to read the data successfully that is sent by Alice if the jamming frequency, $f_J = f_T$. However, a recent study shows that the jammer (Joy) frequency is not necessarily to be the same as Alice’s frequency to disrupt the communication link when a power detector (ZBD) is used as the receiver [39,40]. If the frequency offset ‘$\Delta f$’ between Alice and Joy is within the electrical bandwidth of the ZBD (typically 10-20 GHz) i.e. $|f_T-f_J| \leq \Delta f$, and Joy’s frequency is a continuous tone signal, it will still result in the unsuccessful communication link between Alice and Bob. If $\Delta f$ is beyond the electrical bandwidth of the ZBD, then $f_J$ will result in the pure D.C signal which can be easily filtered using A.C coupling of the electronic components used in the next stage of the detector. In such a scenario, the photonics-based FHSS system can be beneficial as it is possible to tune the THz frequency over a broad spectral range in a short duration. The laser tuning rate can be further improved by using the swept laser as one of the optical sources [41]. The FEC code can be used to retrieve the data when the carrier frequency of Alice falls within the jamming frequency range. This approach is also applicable to multi-tone jammers if their frequencies are out of the jamming offset range. Alternatively, for $f_J \neq f_T$ and ‘$\Delta f$’ less than the electrical bandwidth of the detector, one can add tunable filters to the broadband detector whose bandwidth is similar to the bandwidth of the data signal [42,43]. Here, the frequency tuning rate of the filter must be equal to the hopping rate of the FHSS system.

So far, we have discussed the frequency hopping approaches in the THz wireless systems. Recently, the THz fiber-based communication links are getting attention as they can be used to provide reliable communication in a non-line-of-sight link and precise alignment is generally not necessary when compared with wireless systems [37,44,45]. In particular, the THz fibers can provide additional support to the wireless THz systems. For example, it can be used to route the THz signal from the source to the transmitting antenna (located in the outdoor environment) and the receiving antenna to the detector or signal processing unit, respectively. To achieve better performance for the frequency hopping THz signals, the THz fibers must operate in the single-mode regime, and possess low loss and dispersion within the hopping bandwidth.
Although the THz fibers are highly immune to eavesdropping/jamming attempts, due to the above-mentioned applications, the performance of the THz fiber link must also be studied for the FHSS signals.

In this work, we present the tunable DFB laser-based frequency hopping technique for secure wireless THz communications. While using broad bandwidth THz Schottky diode as the detector, the proposed technique provides a simple solution against the single/multi-tone jamming attack. The paper is organized as follows. As the performance of the THz FHSS greatly depends on the frequency-dependent behavior of the THz transmitter and receiver device, we first present the experimental setup and the channel characterization of the empty system (wireless link) in the frequency range of 110-170GHz. In this setup, we used the uni-traveling carrier photodiode (UTC-PD) as the THz transmitter and the ZBD as the envelope detector. Secondly, we present the calibration of the DFB lasers for different frequency scanning rates and their corresponding frequency tuning range. Next, we study the frequency accuracy as a function of different frequency scanning rates of the laser. Then, we carried out a real-time THz communication experiment by transmitting 6 Gbps data using the frequency hopping spread spectrum technique. Finally, we present the THz subwavelength dielectric fiber link (see Ref. [37] for more information on the fiber) and measured its performance by conducting the THz communication studies using the frequency hopping technique.

2. System description

In Fig. 1 (a), we present the schematic of the photonics-based THz communication setup in which the THz FHSS studies were carried out. A detailed description of the setup is presented in Ref. [37,38]. Briefly, the optical source consists of two independently tunable DFB lasers (TOPTICA Photonics) with a slightly different center wavelength that operates in the optical C-band. The laser beams are then combined using a 3 dB fiber coupler and intensity-modulated (biased at quadrature points) using non-return to zero (NRZ) pseudo-random bit sequence (PRBS) data. The modulated laser beams are then amplified using the Erbium-doped fiber amplifier (EDFA) (Calmar laser) and fed into the photomixer (UTC-PD from NTT Photonics, Inc) for THz generation. A pair of Teflon lenses with a diameter of 50 mm and a focal length of 10 cm was used to collimate and focus the THz signal from the emitter and into the detector antenna, respectively. In the receiver section, a ZBD (Virginia diodes, Inc) was used to detect and demodulate the THz signal (direct detection without offline signal processing). The demodulated baseband signal was then passed through the bias-tee (filters the DC voltage) and amplified by the low noise amplifier (LNA) (Fairview Microwave) with a bandwidth of 3 GHz for further analysis. In Fig. 1 (b), we present the optical spectrum of the two modulated laser beams for the generation of carrier frequencies at 110GHz, 140GHz, and 170GHz, respectively. Here, the output wavelengths of both laser beams were tuned simultaneously around a certain center wavelength. The inset in Fig. 1 (b), presents a typical eye pattern of the optical signal modulated by the 6 Gbps data right before conversion to THz by the photomixer. Furthermore, we find that such an eye pattern is virtually independent of the spectral separation between the two laser emission wavelengths.

It is noted that the THz communication system operates with a bandwidth of 60 GHz (110-170 GHz) and it can be easily switched to a spectroscopy system by disabling the communication unit. Additionally, the signal-to-noise ratio (SNR) of the received THz signal depends on the frequency-dependent behavior of emitter/detector antennas and the propagation loss in the channel [46,47]. Therefore, we must characterize the frequency-dependent performance of the THz communication system by disabling the communication unit i.e., the spectroscopic studies were carried out. Firstly, we characterized the wireless (free-space) channel with the link distance of 1.75 m by measuring the THz amplitude from 110-170 GHz respectively. It is noted that there is no specific reason for setting the link distance to 1.75 m and it is simply convenient for our demonstrations.
A slow scan with the frequency step of 0.05 GHz and the integration time constant of 300 ms was used to record the signal and the normalized spectrum is shown in Fig. 2 (red curve). We see that the normalized THz amplitude was much lower (below 40% by power) at lower THz frequencies (<130 GHz) and increases to the maximum at higher frequencies. This is due to two factors. First, for frequencies below 130 GHz, the output power of the THz emitter and the responsivity of the THz detector was sufficiently lower [37,38]. Second, since the divergence of the THz beam increases at lower frequencies, then, the THz power collected by the collimating lens at the receiver end is expected to decrease at lower frequencies. For example, due to diffraction, the diameter $D_{THz}$ of the THz beam at a link distance, $L$ can be approximated as $D_{THz} \sim L \cdot \lambda_c / D_t$, where $\lambda_c$ is the wavelength of the THz carrier wave and $D_t$ is the lens diameter. While using two identical lenses at the transmitter and the receiver, the power $P_{RX}$ at the link distance, $L$ can be approximated as $P_{RX} = P_{TX} (D_t / D_{THz})^2 \sim P_{TX} (D_t / L \cdot \lambda_c)^2$ where $P_{TX}$ is the transmitted power. For example, for the THz carrier frequencies of 110 GHz ($\lambda_c = 2.725 \text{ mm}$) and 170 GHz ($\lambda_c = 1.763 \text{ mm}$), the beam diameters at the link distance of
$L = 1.75 \text{ m}$, are estimated as $\approx 95 \text{ mm}$ and $\approx 62 \text{ mm}$, respectively which are both larger than the diameter of the collecting lens $D_l = 50 \text{ mm}$ at the receiver. Therefore, the total power collected by the detector at lower carrier frequencies will decrease. In contrast, at higher frequencies, in addition to the lower beam divergence, both the output THz power and the responsivity of the detector increase which results in higher detected THz powers.

![Figure 2](image)

**Fig. 2.** Normalized THz amplitude versus frequency for the free space and fiber-based THz link at the link distance of 1.75 m.

Next, we must expect that at a higher scanning rate of the lasers, the true output laser wavelength at a given time will not be accurately recorded due to the communication delays between the computer and the laser controller. Therefore, the calibration files which map the laser wavelengths and the THz frequency at a slower scanning rate of the laser will not be precise enough for fast scanning. To measure the THz frequency accurately at a higher scanning rate of the lasers in real-time, one can use the molecular absorption lines of any gases (water vapor for example) or organic molecules with several absorption lines ($\sim$ at least 10) within the measurement bandwidth of 60 GHz (in our experiment). To the best of our knowledge, there are no candidates with several absorption lines within the spectral band of 110-170 GHz. Alternatively, one can use the beat pattern due to standing waves that arise between the emitter and detector of the THz wireless systems. From the red curve of Fig. 2 (free-space system), we observe that the frequency difference between the neighboring amplitude peaks of the beat pattern was much smaller ($\approx 0.8 \text{ GHz}$). This is mainly because of the presence of two lenses in the beam path which generates additional standing waves and thereby results in a smaller frequency difference. During the higher scanning rate of the laser, the fluctuation in the THz amplitude increases, and therefore, it is less convenient to use the beat frequency of the free-space system for true THz spectral calibration. On the other hand, one can use the THz fiber link, as there are no passive optics (lenses) used to couple the THz power from the emitter and to the detector, respectively. Therefore, no additional standing waves can be formed and deteriorate the THz amplitude signal. We can take the advantage of the beat frequency in the THz fiber link for THz spectral calibration at a higher laser scanning rate which we assume is equivalent to molecular fingerprinting. The choice of THz fiber is arbitrary and we used the commercial THz subwavelength fiber with air cladding that is fabricated using polypropylene (PP) with a diameter of 1.75 mm for the demonstration [37]. Now, a similar spectral scan between 110-170 GHz was carried out with the THz fiber link that is butt coupled (Teflon lenses were removed here) with the emitter/detector antenna and the normalized THz amplitude is shown in Fig. 2 (see blue curve). We observe that, contrary to the wireless link, the amplitude of the THz fiber link was higher at lower THz frequencies. This phenomenon can be explained as follows. Firstly, in the fiber link, most of the fundamental mode field propagates in the air cladding for lower frequencies...
(lower propagation loss) and is tightly confined in the PP core at higher frequencies (higher propagation loss). Secondly, the material absorption loss increases with the frequency which further decreases the received THz signal at higher frequencies. The detailed characterization of the fiber and the material absorption loss can be found in Ref. [37]. Moreover, the frequency difference between the neighboring amplitude peaks of the beat pattern was higher (∼2.5 GHz) which can be a convenient solution for comparing the THz amplitude at the higher scanning rate of the laser. It is also noted that the THz fiber link discussed above was not only used for the calibration of the true THz frequency at a higher scanning rate of the laser but also, we carried out the FHSS experiments which were demonstrated in the later section of this paper.

3. Experimental results and discussion

3.1. Calibration of the tunable lasers

In this sub-section, we present the calibration of DFB lasers for different frequency scanning rates. The DFB lasers were operated using a microprocessor-based laser controller unit (DLC smart-TOPTICA Photonics) and the input parameters (Set frequency, tuning range, integration time constant, etc.) can be given by the user via the graphical user interface (GUI). The GUI also returns the user with the output values such as estimated frequency, THz photocurrent (output of the ZBD), etc. The ‘estimated frequency’ of the THz signal provided by the GUI was calculated by measuring the instantaneous temperature/current of the laser in real time. As mentioned in the previous section, the calibration of the THz output frequency was carried out for the slow scanning rate of the laser. Therefore, to verify the THz frequency accurately during fast frequency switching, a bi-directional scanning was carried out i.e., the THz frequencies were swept from $f_L$ to $f_H$ (direction 1) and then from $f_H$ to $f_L$ (direction 2) to complete one bi-directional scan. It is expected that the values ‘set frequency’ (defined by the user) and the ‘estimated frequency’ (given by GUI) must be the same. A bi-directional scanning (51 scans in total and each scan was recorded in a separate file) was performed in the spectral range of 110-170 GHz ($f_L = 110$ GHz, $f_H = 170$ GHz) with the frequency step ‘$dw$’ of 0.05 GHz and the integration time constant ‘$dt$’ whose value varies between 0.38 ms and 300 ms respectively. A smaller frequency step size was chosen because the temperature controller cannot provide a reliable reading at a higher rate. The ratio $dw/dt$ is then termed the ‘scanning rate’ of the laser which is varied by changing the integration time constant $dt$. In Fig. 3, we present the ‘estimated frequency’ (as given by GUI) as a function of ‘set frequency’ for different laser scanning rates (131.5 GHz/s, 65.7 GHz/s, 24.75 GHz/s, and 0.15 GHz/s), respectively. It is noted that there is no time delay when the frequency sweep changes its direction from $f_H$ towards $f_L$ and vice versa. From Fig. 3(a), we see that, at a higher laser scanning rate of 131.5 GHz/s and within the THz frequency tuning range of 60 GHz (110-170 GHz), the laser does not reach the state of dynamic equilibrium. It is because of the characteristics of the tunable DFB laser that we have used in this experiment. The DFB laser has a current tuning rate of ∼0.5 GHz/mA and a temperature tuning rate of ∼13 GHz/K which results in the maximum current tuning range of 10 GHz (peak to peak) and the temperature tuning range of ∼600 GHz (Mode hop free tuning range), respectively. So, by appropriately choosing the center wavelength of the lasers (telecom band) and by tuning the temperature, a broad spectral scan from ∼0 - 1.2 THz can be achieved [48]. For the higher scanning rate, the temperature tuning of the laser behaves nonlinearly. At the beginning of the scan, the “set frequency” starts to change (from 110 GHz) but the response time of the temperature tuning was slower which results in the slow variation in the “estimated frequency”. Then, the estimated frequency starts changing linearly until the scan reverses its direction. We observe the nonlinearity again while the scan reverses its direction and then it continues to behave similarly to the previous scan direction i.e., linearly. This repeats back and forth while the lasers attempt to approach the dynamic equilibrium condition. At the reversal of each scan, we observe a hysteresis because the response of the laser to the temperature reversal was slower (cooling and heating) and the command/feedback from the
computer/temperature controller has some delay (~40 ms) in the communication. Both nonlinear variation and the spectral gap (hysteresis) while reversing the scan direction reduces with the decrease in the scanning rate of the laser (see Fig. 3 (a)-(c)). This is due to the linear response of the temperature controller at the slower scanning rate of the laser. Finally, in Fig. 3(d), we see that the “set frequency” and the “estimated frequency” agree well at the scanning rate of 0.15 GHz/s.

![Graphs showing frequency offset for different scanning rates](image)

**Fig. 3.** Measurement of the frequency offset between the set frequency and estimated frequency for different scanning rates of the laser (a) 131.5 GHz/s, (b) 65.7 GHz/s, (a) 24.75 GHz/s and (a) 0.15 GHz/s.

In Fig. 4, we present the maximal frequency tunable range of the THz system as a function of the scanning rate of the laser. The frequency tuning range is defined as the difference between the maximum and minimum frequency while the system scans in one direction (see Fig. 3) i.e., it can be extracted while the system scans from 110 GHz to 170 GHz (direction 1) or vice versa (direction 2) in a bidirectional scan. For a slower laser tuning rate of <10 GHz/s, the maximum frequency tuning range of the system is >50 GHz which is greater than 80% of the scanning window (60 GHz (110-170 GHz)). While increasing the scanning rate of the laser, the frequency tuning range decreases rapidly. Although the frequency tunable range is the same for both directions in a bi-directional scanning, the output THz frequency differs depending on the scanning rate which will be discussed in the next section.
3.2. Measurement of true THz frequency in the THz FHSS system

In the previous section, we showed that there is a large deviation between the ‘set frequency’ and the ‘estimated frequency’ for different scanning rates of the laser. During the THz spectral scanning, the ‘estimated frequency’ from the GUI is true only for the slower scanning rate (smaller frequency step ‘\( dw \)’ and larger integration time constant, ‘\( dt \)’). Due to the time delay in the communication interface between the DFB laser, temperature controller unit, and the computer, the difference between the ‘estimated frequency’ given by the GUI and the ‘true instantaneous THz frequency’ is larger (∼2 GHz) which is especially pronounced at faster scanning rate. In Fig. 5, we present the THz amplitude spectrum that was measured using a fiber link as a function of estimated frequency in a bi-directional scan for different laser scanning rates (131.5 GHz/s, 65.7 GHz/s, and 24.75 GHz/s). For ease of analysis, we present the amplitude spectrum of only the last two scans (from the total of 51 scans) which covers both the directions i.e., direction 1 and direction 2, respectively. Similarly, for comparison, the reference spectrum was obtained for the slower scanning rate of 0.15 GHz/s. As shown in Fig. 5 (a), the tuning spectral range shrinks at faster scanning rates (131.5 GHz/s vs 65.7 GHz/s), while positions of notable spectral features (such as peaks) in the dynamic scans can be ∼2-6 GHz different from those in the reference spectra. While decreasing the scanning rate of the laser, for example at the rate of 65.7 GHz/s and 24.75 GHz (Fig. 5 (b) and (c)), we see that the frequency offset between the measured THz amplitude spectrum and the reference spectrum decreases. By further decreasing the scanning rate of the laser, the frequency offset can be minimized and becomes similar to the reference spectrum. We also notice that at each scanning rate, the THz amplitude spectrum was blue-shifted for both the scanning direction which is due to the communication delays mentioned earlier.

Now, from the results shown in Fig. 5, one can extract the ‘true instantaneous THz frequency’ for each scanning rate of the laser by comparing its amplitude spectrum with the reference. Particularly, the frequency values at several THz amplitude peaks were compared with the reference and fitted using the 1st degree polynomial function within the frequency tuning range, and is shown in Fig. 6. As we observe the nonlinearity in the THz frequency spectrum at every direction reversal, the calculation of true THz frequency is applicable only when the frequency variation is linear. For example, at the scanning rate of 131.5 GHz/s (direction 1), the estimated frequency decreases in the beginning and then starts increasing linearly (see Fig. 3 (a) and 5 (a)). Therefore, the above calculation of true THz frequency is accurate only for the linear region. A similar method can be followed to extract the true frequency for different scanning rates of the laser.
Fig. 5. Measurement of frequency accuracy by comparing the THz amplitude of fiber link for the laser scanning rate of (a) 131.5 GHz/s (b) 65.7 GHz/s and (c) 24.75 GHz/s to the reference (0.15 GHz/s).
3.3. Frequency hopping spread spectrum communication in THz wireless link

In this section, we present the demonstration of the laser-based FHSS technique by carrying out real-time communication experiments. A line-of-sight free space THz communication link over the distance of 1.75 m was established (enabling the communication unit) using two 50 mm collimating and focusing optics (similar to the experimental setup presented in Fig. 1). A careful alignment was carried out to maximize the received THz signal in the frequency range of 110-170 GHz. For comparison with the fiber-based THz link that is discussed in the next section and to avoid the effect of saturation of the receiver, the output power of the THz emitter was purposely set to \(~30\) µW instead of the maximal possible 300 µW at 130 GHz. By working with lower THz power (Emitter Photocurrent: 2.5 mA), we were able to record the reasonable bit errors for frequency hopping demonstration in both wireless and THz fiber links instead of recording no bit errors at all at higher THz powers in case of the fiber links which feature considerably smaller losses. However, in real-life systems, we can certainly increase the THz power to minimize the total bit errors for any scanning rate of the laser. A non-return-to-zero (NRZ) pseudo-random bit sequence (PRBS) with a pattern length of \(2^{31} - 1\) and a bit rate of 6 Gbps was transmitted as the information bits. In this work, the bit rate was limited to 6 Gbps mainly because of the low bandwidth LNA (3 GHz) used in the detector electronics. Data rates can be increased many folds.
by using higher bandwidth LNAs and standard data multiplexing approaches. We must also note that, although the demonstrated bitrate was much lower than the capacity of the 5G/6G systems, even as is, it can find applications in intravehicular communications, uncompressed 4K video transmission, etc.

In general, while carrying out the data transmission at a single carrier frequency, the optimal decision threshold of the received bit was identified by manually balancing the insertion (bit zero is mistakenly identified as bit 1) and omission error (bit 1 is mistakenly identified as bit 0). This results in minimizing the total error (sum of insertion and omission error). The decision threshold at the receiver differs for different carrier frequencies, as it depends on the frequency-specific output power of the transmitter and the responsivity of the detector. In FHSS communications, the choice of varying the decision threshold is not possible due to the fast switching of the carriers. However, one can use the average value of the decision threshold that was measured for each carrier frequency (within the communication bandwidth) in the FHSS communication systems.

Firstly, the bit error rate (BER) for the 6 Gbps data stream was measured for the individual carrier frequencies (static measurement, laser scanning was turned off) that were varied from 100GHz to 170GHz with the frequency step of 3GHz. To record the highly consistent BER in a short measurement duration, the target BER was chosen as $10^{-12}$. Therefore, the measurement duration was set to 3 minutes ($=1/(\text{target BER} \times \text{Bit rate})$). The decision threshold was balanced and the BER was recorded at each carrier frequency. In Fig. 7, we present the decision threshold of the balanced system which varies from -3 mV to +5 mV in the frequency window of 110-170GHz and the average value ($=0 \text{ mV}$) was estimated. The inset in Fig. 7 shows the corresponding eye patterns at several frequencies within the measurement window. As discussed in section 2, the difference in the THz eye amplitude is due to the frequency-dependent output power and responsivity of the detector. In addition, the divergence of the THz beam plays a significant role at lower THz frequencies which minimizes the received power as the size of the aperture is only 50mm (collecting lens).

Next, for comparison with the FHSS system, we carried out similar BER measurements from 110GHz-170GHz with 0mV as the decision threshold. In Fig. 8, we present the BER measurements for 6 Gbps transmission as a function of THz carrier frequency with two different decision thresholds (balanced and average value). We observe that slightly higher bit errors were recorded while using 0mV as the decision threshold. Moreover, the recorded BERs are higher than the FEC limit ($10^{-3}$) for the carrier frequencies below 125GHz. From this experiment, the average BER within the frequency tuning range of 60GHz (110GHz-170GHz) was calculated as $\sim 2.7 \times 10^{-3}$. Next, we carried out the FHSS in the THz wireless communication link. In particular, the BER for the transmission bit rate of 6 Gbps was measured as a function of laser scanning rate. Similar to the previous experiment, the measurement duration was set to 3 minutes at each scanning rate and the BER was recorded as shown in Fig. 9. The inset in Fig. 9 shows the eye pattern that was measured for different frequency hopping rates. We note that, for a slower scanning rate, the measured BER was above the FEC limit and the error rate decreases with the increase in the scanning rate. When the system operates at lower scanning rates, the “estimated frequency” is close to that of the “set frequency”. This means that the difference between the ‘set frequency’, ‘estimated frequency’, and ‘true frequency’ is negligible. Therefore, the frequency hopping at a lower scanning rate covers almost all the frequencies in the scanning window (110-170GHz), including the lower frequencies where BER is very high. In this scenario, one can expect the total BER of the frequency hopping system to be simply the time average of the BERs measured for individual carrier frequencies within the hopping window. From Fig. 8, we can estimate the total average BER as $\sim 2.7 \times 10^{-3}$ as the duration of the data transmission at a given frequency is the same for all the frequencies within the hopping window. This is estimated using Eq. (1). In contrast, at higher scanning rates, the system samples a considerably smaller
Fig. 7. Real-time characterization of the wireless THz FHSS communication system. (a). Balanced decision threshold versus THz frequency. The inset shows the eye pattern for 6 Gbps data at the frequency of 110 GHz, 120 GHz, 130 GHz, 140 GHz, 150 GHz, and 160 GHz, respectively. The white arrow in the eye pattern represents zero mV.

bandwidth mostly at higher frequencies, thus resulting in smaller effective BERs.

\[
BER_{FHSS} = \frac{\int_0^T BER(f(t)) \times dt}{T} \quad (1)
\]

From Eq. (1), \( BER(f(t)) \) is the measured BER at the true THz frequency, \( f \) within the scanning window, and \( T \) is the total scanning period of a single scan. Similarly, at a higher scanning rate, the frequency tuning range falls within the true THz frequencies which results in low BER. For instance, at the scanning rate of 131.5 GHz/s, the THz carrier frequency oscillates between 122 GHz to 135 GHz in one direction and 155 GHz to 142 GHz in another direction (bi-directional scan) (See Fig. 3 (a) and 5 (a)). Therefore, the \( BER_{FHSS} \) will be the average BER measured for the individual carrier frequencies within this bandwidth which is \( \sim 2.7 \times 10^{-4} \).

3.4. Frequency hopping spread spectrum communication in THz fiber link

Next, we present the demonstration of THz FHSS communication using the THz fiber link. As mentioned in the introduction, despite the THz fibers being highly immune to eavesdropping or jamming, they can be generally used to route the frequency-hopped wireless THz signals in an environment with a complex geometrical path. Therefore, the performance of the THz fibers in
**Fig. 8.** Measured BER for 6 Gbps data using balanced decision threshold and average decision threshold (0 mV) in a free-space THz communication system.

**Fig. 9.** Measured BER versus scanning rate of the laser in a wireless THz FHSS system. Inset: Measured eye patterns for the bit rate of 6 Gbps for different scanning rates. The white arrow mark in the inset represents 0 mV.
an FHSS system is essential. In what follows, we first present the theoretical characterization of the THz fiber. A rod-in-air fiber is the simplest form of solid core fiber in the THz spectral range which can be fabricated using low loss polymers such as polypropylene (PP), Teflon, polyethylene, etc. In general, the refractive index (RI) of the polymers is constant in this spectral range, however, the bulk material losses increase polynomially with the frequency. In our studies, the PP fiber of 1.75 mm diameter and 1.75 m length was considered (same as the THz fiber presented in section 2). Similarly, the bulk RI and loss of PP are 1.485 and 2.36 dB/m (128 GHz) respectively [37]. The numerical simulation was carried out using COMSOL Multiphysics in the frequency range of 110 GHz to 170 GHz which corresponds to the frequency spectrum of the uni-traveling career photodiode (THz emitter) and the ZBD (THz detector).

![Fig. 10. (a). The normalized electric field profile of the fundamental mode supported by the fiber at 110 GHz, 140 GHz, and 170 GHz. (b). The effective RI and normalized power fraction of the fundamental mode that is contained inside the solid core.](image)

In Fig. 10 (a), the normalized electric field profiles of the fundamental mode supported by the fiber are presented for the carrier frequency of 110 GHz, 140 GHz, and 170 GHz, respectively. Similarly, the effective index and the normalized power fraction of the fundamental mode that is confined within the solid core are shown in Fig. 10(b). We see that the power fraction inside the solid core increases with the frequency. Therefore, the modal loss also increases along with the frequency approaching the bulk material loss of PP which results in the decrease of the received THz power at higher frequencies. In addition to the modal loss, the frequency-dependent excitation efficiency and dispersion determine the maximal link length and bit rate supported by the fiber. Although a higher excitation efficiency can be achieved for the fiber in the broad spectral range, the dispersion reaches a maximum of ~10 ps/(THz.cm), particularly at lower THz frequency (110 GHz) [37]. Therefore, the maximum bit rate supported by the THz fiber in an FHSS system is mainly limited by the modal absorption loss and dispersion.
Next, we carried out the THz communication experiments by inserting the THz subwavelength fiber with a link length of 1.75 m. The fiber was butt coupled to the horn antenna of both emitter and detector, respectively which is followed by careful alignment to maximize the received THz power at the detector. Similar to the experiments presented in subsection 3.3, the BER was recorded for the bit rate of 6 Gbps for the carrier frequencies in the range of 110 GHz-170 GHz with the step of 3 GHz. In Fig. 11 (a), we present the decision threshold of the balanced system which varies in the range of +4 mV to +24 mV. We then compute the average value of the decision threshold (11 mV) as shown in Fig. 11(a). In Fig. 11 (b), we present the measured BER (measurement duration: 3 minutes) as a function of carrier frequency in the window of 110 GHz-170 GHz for both the decision thresholds (balanced decision threshold and average value (11 mV)). As we see in Fig. 11 (a), there is a difference of ∼7 mV between the average and balanced decision thresholds for the carrier frequency of >165 GHz. i.e. The decision thresholds for the balanced system were smaller than the estimated average value which results in more insertion errors (digital bit zero is mistaken as bit 1). Moreover, the difference in the BER between the measured frequencies was larger and no errors were recorded at certain frequencies within the measurement duration which is due to the combined effects of peaks of the beat pattern, THz power, modal loss, dispersion, and responsivity of the detector, respectively. It is also evident from the eye pattern presented in Fig. 11 (c). The average BER calculated for the THz fiber link with the decision threshold of 11 mV is ∼2.3 × 10^{-4} which is one order better than the free-space link.

Then, similar to the wireless THz FHSS communication link, we carried out the BER measurements for THz fiber-based FHSS communications by varying the laser scanning rate which is shown in Fig. 12. The measurement duration for the BER was set to 3 minutes for each scanning rate. As predicted, for the slower scanning rate, the measured BER was in the range of ∼2 × 10^{-4}. Since, for the faster scanning rate, the frequency of oscillation is between ∼122 GHz to 135 GHz in one direction and ∼155 GHz to 142 GHz in the other direction, the measured BER agrees well with the average BER that is estimated from Fig. 11 (b) which is ∼1 × 10^{-5}. Therefore, we also confirm that the THz subwavelength dielectric fiber-based FHSS communication link outperforms the wireless link in short-range communications.
Fig. 11. Real-time characterization of fiber-based THz FHSS communication system. (a). Balanced decision threshold versus THz frequency. (b). Measured BER for 6 Gbps data using balanced decision threshold and average decision threshold (11 mV). (c). Eye pattern for 6 Gbps data at the frequency of 110 GHz, 120 GHz, 130 GHz, 140 GHz, 150 GHz, and 160 GHz respectively. The white arrow mark in the eye pattern represents 0 mV.
Fig. 12. Measured BER versus laser scanning rate in a fiber-based THz FHSS system. Inset: Measured eye patterns for the bit rate of 6 Gbps for different scanning rates. The white arrow mark in the inset represents 0 mV.

4. Conclusion

To conclude, in this work, we presented a detailed experimental characterization of a tunable laser-based frequency hopping spread spectrum technique in THz communications. Firstly, we showed that the performance of the THz FHSS technique greatly depends on the frequency-dependent behavior of the emitter and detector antennas. Secondly, we present that, depending on the scanning rate of the laser, the frequency tunable range varies rapidly. The frequency tunable range decreases significantly for the fast scanning rate and also influences the output frequency accuracy of the system. We then demonstrate the THz FHSS system by transmitting 6 Gbps data in both wireless and THz fiber links and verified that the measured BER in an FHSS link is the average BER that was recorded for the individual carrier frequencies within the frequency tunable range. Finally, we conclude that in an incoherent THz communication with a broadband power detector, the proposed technique provides a novel and compact solution against the single/multi-tone jamming attack (without noise modulation) which is highly attractive for establishing the next-generation secure communication links. Although the photonics-based approach generates only a linear frequency hopping pattern, it is still advantageous when compared to the commonly used THz communication systems with the fixed carrier frequency. Furthermore, two potential improvements to the current system (not studied in this paper) could increase the impact of the proposed technique. Firstly, by using a tunable narrowband filter before the detector with a bandwidth and tuning rate similar to those of the transmitter, the proposed photonics-based frequency-hopping approach could offer high resistance against the single/multi tone jamming signals (with or without noise modulation). Secondly, by replacing one of the lasers with a fast tuning swept laser, the scanning rates, as well as the actual scanning bandwidths can be greatly improved. In conclusion, we believe that the proposed technique could have a significant impact on the development of secure THz communication systems.

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**Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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