Optical heterodyne AND operation as emulation of physical layer security at wireless communication

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Abstract As a physically secured wireless communication method, a novel configuration which deduces ANDed data decoded from heterodyne detection between two wireless data streams was proposed. As a feasibility experiment, the demonstration of a heterodyne AND operation was conducted by devising an optical system to emulate our novel wireless system. Experimental results testified the principle of our proposed physical layer security.

key words: millimeter wave, terahertz wave, wireless communication, physical layer security
Classification: Optical hardware

1. Introduction

With the rapid spread of IoT devices and the introduction of 5G, the demand for wireless communication with high security as well as high data rate is increasing for Beyond 5G (6G) [1, 2, 3, 4, 5, 6]. Among wireless communication security techniques, physical layer security, which can provide unbreakable, provable and quantifiable secrecy from an information-theoretical point of view, has drawn significant attention [6, 7, 8, 9, 10, 11]. Two primary attacks at the physical layer of a wireless network are jamming and eavesdropping [12, 13]. As for the way to prevent eavesdropping, using terahertz (THz) waves as carriers is effective way because they can support higher link directionality and possess higher resilience to eavesdropping due to their shorter wavelength [14, 15, 16, 17].

We have ever realized the beam forming and steering of THz waves at a carrier frequency of 300 to 700 GHz by combining THz waves in space radiated from arrayed un-traveling carrier photodiodes (UTC-PDs) [18] integrated with antennas [19, 20, 21]. Based on this THz beam management technologies, for enhancing a physical layer security at wireless communication, we have invented a detection system which deduces an ANDed signal from two wireless signals as described in the next section. The configuration reduces a possibility for third parties of detecting the real data from each wireless signal. This system is enabled by THz coherent detection technologies [22, 23, 24, 25] and our novel high-frequency wave beam steering via an UTC-PD/antenna array [19, 20, 21]. In this letter, as an emulation of the proposed wireless heterodyne AND operation system, we construct an optical heterodyne AND operation system and experimentally demonstrate the feasibility of the secured communication mechanism.

2. Proposed high-security wireless communication system configuration

Fig. 1 shows the conceptual diagram of our novel high-security THz wave communication system. At the transmitter end, the original data sent by an electrical signal is decomposed into two data streams by the encoder so that the AND of the decomposed data coincides with the original data. Each data stream is put on a two-tone lightwave with a frequency difference of several hundred GHz by an optical intensity modulator. Each two-tone lightwave has a different frequency difference with each other. The modulated optical signals are converted into electrical signals with frequencies equal to the frequency differences of the two two-tone lightwaves via photomixers such as UTC-PDs.

Each electrical signal is radiated from an UTC-PD/antenna array and combined in space to form a THz beam. The...
beams from the transmitters are steered individually so that they overlap and are received at the desired location. The mixer in the receiver generates a beat signal from the two THz beams by heterodyning. Here, the phase of the beat signal is not stabilized because of the free-running lightwaves but it causes little influence on the following envelope detection, which composes the original data as the AND of the two decomposed data on each THz beam. To obtain a correct AND signal, the receiver needs not only to be at an area where two THz waves overlap, but also at a position where the two data from two transmitters are in the same data phase. For example, for a 10-Gbit/s signal, a phase-matched data pair can be detected only at the desired location with a positioning precision of several centimeters. Therefore, this configuration can enhance security of conventional wireless systems.

The key technologies of the proposed configuration described above are the beam steering at the transmitter end and the AND operation at the receiver end. In the following section, the principles of these technologies are discussed.

2.1 THz beam steering technology
The application of a phased array is a well-known technique with which to steer electromagnetic waves with high frequencies such as millimeter waves or THz waves [26, 27, 28, 29, 30]. Our arrayed UTC-PDs/antennas array [19, 20, 21] is a type of phased array whose phases are shifted by tuning phases of lightwaves before photomixing. We have successfully tuned them with optical delay lines. Fig. 2 shows the angular distribution of THz wave power radiated by four arrayed UTC-PDs/antennas at 600 GHz. In this experiment, we tuned optical delay lines and controlled the peak power position of THz beams between -14 degree and +18 degree. Fig.2(a) and (b) shows angular distributions of the THz beam when the peak was set to -14 degree and +18 degree, respectively. From this experiment, we confirmed that a 600-GHz-wave beam can be controlled within an angle as wide as 32 degrees by optical phase tuning.

By using these THz beam management techniques, we expect the following scenario as an example shown in Fig. 3. The proposed wireless system would be installed in a hall for an event venue. It consists of several transmitters which steer the beams. These transmitters are positioned so that a pair of beams can be overlapped at any location in the hall. The two received data streams have the same data phase and are correctly decoded to the original data at the specific area which is, for example, several centimeters squared in the case of a data rate of 10 Gbit/s. Therefore, the system realizes high-level physical layer security even in an open space.

2.2 Heterodyne AND operation between two THz beams
Fig. 4 shows the conceptual diagram of the encoding/decoding mechanism we have proposed. The electric fields of two THz beams radiated from transmitters are written as

\[ E_1 = A_1 \exp\{j(2\pi f_{RF1} t + \varphi_1)\} \]

\[ E_2 = A_2 \exp\{j(2\pi f_{RF2} t + \varphi_2)\} \]

where \(A_1\) and \(A_2\) represent Data 1 and Data 2 or the amplitudes of the electric fields, \(f_{RF1}\) and \(f_{RF2}\) represent
the carrier frequencies of the beams, and \( \varphi_1 \) and \( \varphi_2 \) represent initial phases. From Eq. (1) and Eq. (2), output power of the mixer as a receiver is described as
\[
P \propto |E_1 + E_2|^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(2\pi(f_{RF1} - f_{RF2})t + \varphi_1 - \varphi_2)
\]  (3)
In the Eq. (3), \( A_1A_2 \) is the product of the amplitudes of the two beams; this is regarded as the ANDed signal of the two beams by heterodyne detection. For example, only when \( A_1 \) and \( A_2 \) are “high” level (expressed as “1” of binary data in Fig. 4) at modulated signals, will the amplitude of the ANDed signal be “high” level (expressed as the oscillation part of ANDed signal in Fig. 4). In addition, the carrier frequency of the output signal is described as \( f_{RF1} \) - \( f_{RF2} \), which means the carrier frequency of the output signal is equal to the frequency difference between those of the two beams. The frequency difference is just an intermediate frequency \( f_{IF} \) resulting from heterodyne detection. From the above-mentioned scheme, the “high”-level oscillation of the ANDed signal with the frequency of \( f_{IF} \) only occurs at the overlapping part of “high” levels of two beams by heterodyne AND operation. Therefore, this system can enhance a physical layer security because the original data can be detected only at the location where two signals overlap in the same data phase as each other.

3. Optical AND operation for feasibility demonstration

To testify the above concept, an optical heterodyne system was configured to emulate the wireless heterodyne AND operation as shown in Fig. 5. Two lightwaves in 1550-nm band are used as the carriers, and a photodiode is utilized as a photomixer which operates as the mixer in wireless setup. The two lightwaves, whose frequency difference is 10 GHz, are independently modulated to form a 500-ns-wide (1-MHz) rectangular wave. They are coupled at an optical coupler (OC) and introduced into the photodiode, which generates a 10-GHz beat signal. Here, the phase of the beat signal is not stabilized because of the free-running lightwaves but it causes little fluctuation of the following detected power. Then, as the ANDed signal, the envelope of the beat signal is detected by an envelope detector, and the decoded signal is observed at an oscilloscope. To confirm the optical AND operation by the photomixer, an optical delay is introduced into one of the optical paths so that the two incident waveforms shift to or from each other.

Fig. 6 shows the expected waveforms of the AND operation in this experiment. When there is no delay, lightwave 2 has the same waveform as that of lightwave 1. Therefore, according to the AND operation scheme in the previous section, a 500-ns-wide rectangular wave would be observed as the ANDed signal at the oscilloscope. Whereas, when lightwave 2 is delayed by 300 ns, a 200-ns-wide rectangular wave would be observed as the ANDed signal. Therefore, the heterodyne AND operation could be testified by observing the width of the heterodyned signal.

4. Experimental result

First, without an optical delay, two lightwaves (lightwave 1 and lightwave 2) with the same rectangular waveform, as shown by the upper two waveforms in left-hand side of Fig. 7, were input into the photomixer. The output voltage
observed at the oscilloscope was confirmed to have the same waveform as the 500-ns-wide incident optical waveforms, as shown by the lower waveform in the figure. Then, one of the lightwaves (lightwave 2) was optically delayed by 300 ns, as shown by the upper two waveforms in right-hand side of Fig. 7. The waveform of the output voltage, shown by the lower waveform in the figure, became a 200-ns-wide rectangular wave. These results are consistent with the expected AND operation shown in Fig. 6. This confirms that heterodyne AND operation between two optical carriers can be conducted by the photomixer in combination with the envelope detector. In this experiment, the two lightwaves have similar intensities. Even with unbalanced intensities of these lightwaves in a real scenario, the signal will appear only at their overlapping part as the ANDed signal because of heterodyne detection. These experimental demonstrations testify the feasibility of our proposed physical layer security communication system.

![Waveform Diagram](image)

**Fig. 7** Observed waveforms of optical AND operation experiment.

5. Conclusion

A novel high-security wireless communication configuration based on AND operation between two carriers at the physical layer was proposed. As a feasibility demonstration, an optical heterodyne AND experiment which emulates wireless heterodyne AND operation was constructed. The experimental result showed the ANDed waveform between two incident optical waveforms which testifies the expected AND operation.

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