An Investigation about All-optical Millimeter Wave Generation Technology for High-speed Communication

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Abstract. With the advent of the network information age, users have higher and higher requirements for the bandwidth and capacity of communication systems. Traditional cellular mobile communications can no longer meet the needs of modern communication systems. It is necessary to find a communication system with larger capacity, higher bandwidth and higher transmission rate. Millimeter wave (MMW) communication has high bandwidth, large capacity and high signal transmission rate. Nowadays, all-optical MMW technology generates high-frequency MMW signals in optical domain, which has become a research hotspot of MMW signal generation technology at home and abroad. In this paper, three typical all-optical MMW generation methods are discussed, including direct modulation method, optical heterodyne method and external modulation method. The advantages and disadvantages of each method are analyzed, and the development prospects of the all-optical MMW generation technology are prospected. It is helpful to research new optical MMW technology in the future.

1. Introduction
With the advent of the network information age, the communication methods of communication users have changed and the communication traffic has increased. Traditional cellular mobile communication is unable to meet the needs of the system[1]. With the development of modern Internet technology and the popularization of various smart terminals, mobile data traffic will explode in the future [2], leading to higher and higher requirements for communication users on the bandwidth and capacity of the communication system.

In modern communication systems, most services are concentrated in relatively low frequency bands below 6GHz [3], making many communication services only use frequency band resources that are rarely used, which severely limits the high-quality development of the system. The data rate that the first- and second-generation mobile communications can transmit is only tens to more than 100,000 bits per second, and the data rate that the third-generation mobile communications can transmit is only 2 megabits per second, which is far from the requirements of broadband communications. The fourth-generation mobile communication technology provides a broadband wireless network that cannot be satisfied by the third-generation mobile communication. Therefore, in order to reduce the waste of resources, it is necessary to find ways with larger capacity, higher bandwidth and higher transmission rate. If the frequency resource band above 30GHz can be used efficiently to transmit signals, not only can the waste of resources be reduced, but also ultra-wideband wireless access can be realized [4].

In order to meet the needs of users for network bandwidth, millimeter wave (MMW) communications have attracted attentions. Compared with the fourth-generation mobile communication system, MMW communication has high bandwidth, large capacity and high signal transmission rate. Because of the high price of its related hardware, MMW communication cannot be used in civil communication systems
on a large scale[5]. Nowadays, the all-optical MMW generation technology generates high frequency MMW signals through an all-optical method, which overcomes the limitations of the response frequency and bandwidth of electronic frequency multipliers, and it is low in cost, simple in structure, and easy to generate high performance millimeter waves with low phase noise. It has become a research hotspot of MMW signal generation technology at home and abroad[6]. In this paper, several typical all-optical MMW generation methods are investigated and compared in detail.

2. All-optical MMW generation methods Key technologies

According to the principle of MMW generation, the all-optical MMW technology can be divided into four categories: direct modulation method[7], optical heterodyne method[8] and external modulator modulation method[9].

2.1. Direct modulation method

Among the all-optical MMW generation technologies, the direct modulation method is the most direct and simple. Only a semiconductor laser is needed to realize the modulation function, and no additional photo/electrical modulator is needed to modulate the carrier.

The structure diagram of the direct modulation method is shown in figure 1, the baseband signal is to digitally encode the radio frequency signal, and then transmit it to the input end of the laser through an optical fiber. After receiving the baseband signal, it is loaded on the drive current of the laser, and then the drive current is affected by the baseband signal and change. The baseband signal directly drives the semiconductor laser to generate multiple optical sideband signals. The frequency of each sideband signal is determined by the frequency of the baseband signal and the center frequency of the laser. The baseband signal is directly used to control the laser drive current to achieve the purpose of modulation. Finally, the beat frequency is performed in the photo detector (PD)to generate the desired MMW signal.

![Figure 1 Direct modulation structure diagram](data)

The direct modulation method has the advantages of simple structure, minimum required equipment, low cost, and easy implementation. In the entire MMW generation system, the direct modulation method uses only one laser, so the requirements for the laser are very high, and the frequency and power tuning of the radio frequency signal are relatively limited. However, due to the inherent relaxation oscillation and frequency chirp characteristics of the semiconductor laser, serious nonlinear distortion will occur, resulting in small modulation bandwidth, low frequency response and other issues that affect the quality of the generated MMW. Therefore, the direct modulation method is only suitable for low-frequency communication systems, and the signal transmission distance is relatively short.

2.2. Optical heterodyne method

The optical heterodyne method is an effective method for generating high-frequency optical MMW signals. Its main principle is to generate two light waves with a frequency difference equal to the radio frequency signal, and load the baseband signal to be transmitted on one of the light waves.

The optical heterodyne structure is shown in figure 2. The simplest optical heterodyne method is to generate two light waves of different frequencies from two incoherent single longitudinal mode lasers, which are coupled in a coupler and transmitted through an optical fiber, and finally in a PD. After beating by the PD, it will output a microwave signal whose frequency is the difference between the frequencies of the light waves emitted by the two incoherent single longitudinal mode lasers [10]. The use of two
lasers makes the generated light wave frequency and its difference have better tunability, so it can generate a higher frequency MMW signal, and its bandwidth can reach the maximum detection frequency range of the PD [12].

![Diagram of heterodyne method](image)

Figure 2. Diagram of heterodyne method

The optical heterodyne method has a simple structure, high signal frequency, strong dispersion resistance, low power consumption, and flexible frequency. Through the structure diagram, it can be seen that this method requires two lasers, and the system construction cost is much higher. And the two lasers are independent of each other, so there is no phase coherence between the light waves generated by the two lasers.

Due to the inherent problems of the laser, the phase of the obtained MMW signal will inevitably change randomly. Moreover, the linewidth and output wavelength of the laser will also change due to changes in its working environment, resulting in changes in its working current. Even the smallest current change will have an adverse effect on the frequency, amplitude, phase noise, signal-to-noise ratio and other performance of the generated MMW signal. In order to solve the problem that the light waves emitted by the two lasers in the MMW generation scheme of the heterodyne method can achieve the stable effect achieved by the above parameter matching, corresponding improvements have been made to it.

In practical applications, in order to enhance the coherence of the phases of two light waves at different frequencies, technologies such as optical injection locking, optical phase-locked loop, and optical injection phase-locked loop are generally used.

2.2.1. Optical injection locking technology.

The optical injection locking technology combines the direct modulation method and the heterodyne method. The principle of optical injection locking technology is shown in figure 3, the first half adopts the principle of direct modulation method to generate MMW, and the principle of heterodyne method is used to generate MMW between the two couplers. The light wave generated by the direct modulation method passes through the first coupler, and the power is transmitted to the two slave lasers to select the desired optical sideband from a series of optical sidebands. Then the two signals are coupled on the second coupler. The part between the two couplers is the principle of optical heterodyne generation of MMW. The optical signal output by the coupler is photoelectrically detected in the PD to generate the target MMW signal.

![Generation principle of microwave signal based on optical injection locking](image)

Figure 3. The generation principle of microwave signal based on optical injection locking

This scheme combines the advantages of the two methods [14]. It is very difficult to find two lasers whose phases of the lasing light field are completely correlated. However, it is relatively easy to achieve the phase synchronization of the lasing light fields of the two lasers (master and slave lasers) by using
the optical injection locking process. The phases of the lasing light fields of each laser will be completely correlated. The injection locking process itself has the effect of selective amplification. By using lower frequency modulation signal light to inject into the slave laser, and select and amplify its high-order sidebands, high-frequency optical microwave signals (high-order sidebands and carrier beat frequencies) can be obtained[16].

2.2.2. Phase-locked loop technology.
The characteristic of the phase-locked loop technology is to connect the phase detector and the slave laser through a circuit filter to form a feedback loop. The feedback loop can achieve the purpose of phase locking between the master laser and the slave laser [18]. The structure diagram is shown in figure 4, which is mainly composed of master-slave laser, coupler, PD, phase detector, reference microwave signal RF and electric loop filter.

![Figure 4. Phase-locked loop structure](image)

The light wave signals from the master and slave lasers are coupled by the coupler and then processed by PD to obtain MMW signals. The phase difference signal between the MMW signal and the reference microwave signal obtained by the phase detector is detected and processed, and the electrical domain filtering process is performed on it in the electrical loop filter, and it is fed back to the slave laser. The slave laser adjusts its operating current according to the feedback information received. After adjustment, the phase difference between the output light waves of the master and slave lasers becomes smaller and smaller, so as to achieve phase lock [19].

The optical phase-locked loop method adjusts the phase incoherence problem existing in the heterodyne method, and the generated MMW signal has the advantages of low phase noise and stable frequency. Although the MMW generated by this method has obvious advantages, it also has many disadvantages. Due to the complex structure of the phase detector in the link, the composition of the entire system is more complicated, and the requirements for system equipment are also higher. The line width of the laser, the line width of the beat signal, and the peak power of the signal all have a great influence on the phase locking effect. The line width of the MMW signal generated by the optical phase-locked loop method is equal to the sum of the line widths of the two master and slave lasers. Therefore, in order to obtain a small line width MMW signal, the master and slave lasers use narrow line width lasers. Although this ensures effective phase lock, it reduces the maximum power of optical fiber transmission, which in turn affects long-distance transmission. And the system cost has also increased.

2.2.3. Light injection phase lock technology.
The optical injection phase-locked method was first proposed by A. J. Seeds in 1999. The special feature of this method is that it combines the technical advantages of optical injection-locked method and optical phase-locked loop method to generate MMW. The light injection phase-locking method makes it possible to effectively achieve phase-locking of wide-linewidth lasers[21].
The principle diagram of optical injection phase locking is shown in figure 5, where the solid lines form the main link and the dotted lines form the feedback loop. In the main link, the coupler divides the light wave power output by the master laser into two channels, one is connected to the PD through the slave laser 1; the other is modulated by the electro-optic modulator to connect the signal to the slave laser 2. Then the two light waves emitted from the laser are coupled and processed by the PD to output MMW signals. In the feedback loop, the MMW signal and the reference signal output by the PD are sent to the phase detector and the phase difference between the two signals is detected, and then the phase difference signal is fed back to the slave laser 2 through the loop filter. After receiving the feedback information from laser 2, the corresponding processing is performed to reduce the phase difference between the two light waves emitted from the laser. After multiple feedbacks, the phase difference is as close to zero as possible, so as to minimize the phase noise and improve the signal quality[23].

2.3. External modulator modulation method

The optical heterodyne method is highly dependent on the laser, and the quality of the MMW signal generated is also easily affected by the laser. In order to improve the quality of the generated MMW signal and enhance its stability, many scholars have begun to shift their attention from the laser to the modulator.

As shown in the figure 6, the emitted light wave enters the modulator, drives the modulator through a low-frequency radio frequency signal and a DC voltage, and the resulting optical sideband signal carries the amplitude and frequency information of the radio frequency signal. Finally, the optical-to-electrical conversion process is performed by the PD, and the MMW signal with a frequency of several times is obtained at the output[24].

The external modulation method uses the optical carrier of the same laser to output an optical signal with multiple-order sidebands, which has strong phase correlation and ideal system phase noise [25], which makes the quality of the generated MMW signal much better. And by changing the value of the DC voltage, different modulation methods can be realized to obtain the desired optical sideband signal.
2.3.1. Double Side Band (DSB) Modulation.

The modulation principle diagram and the optical MMW schematic diagram of DSB are shown in Figure 7. In the DSB modulation system, the baseband signal is mainly modulated to the central optical carrier and two first-order sidebands (under a small modulation index, other high-order harmonics can be very good Is suppressed), generates an optical MMW signal with a frequency twice the frequency of the input radio frequency local oscillator, and transmits it to the receiving end through a single-mode fiber (SMF), is detected by the PD. Then it passes through the band pass filtering can generate an electric MMW signal with a baseband signal and a frequency of $2\omega_m$.

When the light wave modulated by DSB is transmitted in the optical fiber, due to the existence of fiber dispersion, the dispersion effect produces different phases for different frequency components, so that the two-beat frequency radio frequency signals have different phases, the power of the radio frequency signal will change. As the transmission distance and carrier frequency show periodic changes, the transmission distance of the DSB system is limited.

![Figure 7 (a). DSB modulation principle diagram & (b) DSB MMW diagram](image)

2.3.2. Single sideband (SSB) modulation.

If PS (phase shift) is used and set phase difference to $\pi/2$, and the DC offset voltage difference is still $V_m/2$, the generated optical MMW signal will be selectively suppressed, producing an optical SSB signal containing only the central optical carrier and a first-order sideband [26] [27].

![Figure 8 (a). SSB modulation principle diagram & (b) SSB MMW diagram](image)

The principle of SSB modulation is shown in Figure 8. In the SSB modulation system, the baseband signal is mainly modulated to the central optical carrier and one of the first-order sideband (the other first-order sideband is suppressed, and at the same time, under a small modulation index, other high-order harmonic fields can be suppressed.) The optical MMW signal with the frequency of the input radio frequency local oscillator frequency is generated, transmitted to the receiving end through a SMF, detected by the PD. Then it passes through band-pass filtering. An electric MMW signal with a baseband signal and a frequency of $\omega_m$ can be generated.

When the light wave modulated by SSB is transmitted in the optical fiber, since only the center carrier and one sideband carry the baseband signal, only one radio frequency signal is generated when the receiving end beats the frequency, thus avoiding the periodic fading effect in DSB modulation system. Due to the existence of fiber dispersion, the time for the signals carried by the two frequency components of the optical MMW to reach the receiving end is different, and the information carried on the sidebands will deviate from the information carried on the central optical carrier, resulting in loss of
synchronization in time. The symbols of the final demodulated baseband signal are narrowed or even disappear, and the baseband signal cannot be demodulated. This phenomenon is called "symbol narrowing effect" or "symbol time shift effect". When the SSB signal is transmitted in the optical fiber, as the distance increases, the relative time shift of the signal symbol carried on the sideband and the center carrier will become larger and larger. When it reaches one symbol width of the baseband signal, the signal will disappear completely, and the original information to be transmitted in the system can no longer be recovered at the receiving end. Therefore, this effect caused by fiber dispersion limits the longest distance the signal can be transmitted in the SSB modulation system.

2.3.3. Suppress carrier double-sideband (OCS) modulation.

In the DSB modulation system, the RF local oscillator frequency is reduced to half of the original frequency, PS (phase shift) makes their phase difference $\pi$, and the DC offset voltage difference is still $V_n$, then the generated optical MMW signal will be suppressed and only two first-order sidebands are generated [26][31]. The modulation principle diagram and optical MMW schematic diagram are shown in Figure 9.

![Figure 9 (a). OCS modulation principle diagram & (b) OCS MMW diagram](image)

In the OCS modulation system, the baseband signal is mainly modulated to two first-order sidebands (the central optical carrier is suppressed, and at the same time, under a small modulation index, other high-order harmonic fields can be suppressed well). The optical MMW signal whose frequency is twice the frequency of the input LO is transmitted to the receiving end through a SMF, detected by the PD, and then subjected to band-pass filtering to generate an electrical MMW signal with frequency $\omega m$.

When the OCS modulated light wave is transmitted in the optical fiber, since only two sidebands carry the baseband signal, only one radio frequency signal is generated when the receiving end beats the frequency, thereby avoiding the periodicity caused by the fiber dispersion in the DSB modulation system. Due to the existence of fiber dispersion, the signals carried by the two sideband components of the optical MMW take different time to reach the receiving end. The information carried on the upper sideband will deviate from the information carried on the lower sideband, resulting in loss of synchronization in time. This makes the symbols of the finally demodulated baseband signal narrow or even disappear, and the baseband signal cannot be demodulated. This phenomenon is the same as the "symbol narrowing effect" or "symbol time shifting effect" that appears in the SSB modulation system. In other words, this effect caused by fiber dispersion also limits the longest distance the signal can be transmitted in the OCS modulation system.

Compared with DSB and SSB, OCS modulation technology has unique advantages. In the OCS modulation system, two sidebands generate beat frequencies at the receiving end. In this technology, the frequency of the RF LO signal required to modulate the optical signal is only half of the DSB and SSB.

3. Conclusions

All-optical MMW generation technology is one of the important research directions in microwave photonics. In this paper, several typical all-optical MMW generation methods are discussed, which will help to research new optical MMW technologies in the future. The main contents are as follows:

(1) The direct modulation technology has been studied. The main advantages are fewer devices and simple structure. However, due to the relaxation oscillation characteristics and frequency chirp
characteristics of the laser itself, this MMW generation method can only be used in low-frequency systems and has a short transmission distance.

(2) The MMW signal generated by the heterodyne method is not only less affected by the fiber dispersion effect, high frequency and continuously adjustable, but also has a good signal-to-noise ratio. This method uses two independent lasers to make the output optical signal phase incoherent, resulting in particularly unsatisfactory system noise. Although the principle has been improved and a good signal-to-noise ratio has been obtained, it has brought about problems such as complex system structure and high cost.

(3) The external modulator method not only provides high modulation bandwidth, good stability, easy configuration and good phase coherence, but also has the advantages of higher stability and lower phase noise. At present, more and more researchers have chosen as the method to generate high-quality millimeter waves.

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