Advance in Microwave Photonics

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Abstract:
Microwave photonics is a combination of microwave and photonics in concepts, devices and systems. Its typical research involves optical generation, processing and conversion of microwave signals, as well as distribution and transmission of microwave signals on optical links. Research achievements of microwave photonics have promoted the development of some new technologies, including Radio over Fiber (RoF) communication, subcarrier multiplexing and fiber transmission in Cable Television (CATV) system, optical controlled beam forming network with phased array radar and measurement technologies in microwave frequency domain.

The introduction of Wavelength Division Multiplexing (WDM) technology and the invention of Erbium-Doped Fiber Amplifier (EDFA) drive the rapid development of optical communication. Optical fiber communication has many advantages, such as low loss, immunity to Electromagnetic Interference (EMI), ultra-wideband, and capability of multiplexing in wavelength, space and polarization.

Meanwhile, increasing demands for wireless communication capacity promote the development of microwave technologies. The advantages of microwave communication include transmission in any direction, ease of constructing and reconfiguration and interconnection with mobile devices. Besides, with cellular systems adopted, high spectral efficiency can be achieved in microwave communication. However, the limited bandwidths of current microwave bands have become a great challenge, so people are considering new bands, i.e. 30-70 GHz. Having high access rate and operating on license-exempt band, 60 GHz Radio over Fiber (RoF) system is becoming popular for broadband access.

The merging of optical technology and microwave technology has become an important and inevitable trend. The common theoretical basis enables microwave devices and optoelectronic devices to use the same materials and technologies and be integrated onto one chip. This propels the combination of the two technologies and the birth of a new cross-discipline: Microwave photonics.

The concept "microwave photonics" was first proposed in 1993[1]. Its research covers all fields related to microwave and optical technologies[2], particularly focusing on the following two aspects. The first aspect is to solve the problems arisen in the development and application of traditional optical communication technologies in microwave bands by researching laser, optical modulator, amplifier, detector, fiber transmission link, etc. The second aspect is to use optoelectronic devices to generate and control microwave signals, including microwave sources for optical generation, microwave photonic filter, optical domain-based microwave amplifier, and optically-modulated microwave signals.

1 Key Technologies in Microwave Photonics

1.1 Optical Microwave Signal Generation

The development of microwave communication towards such high frequencies as 30-70 GHz is a great challenge for traditional microwave devices. In this situation, using optical technologies to generate microwave signals seems a very attractive solution. There are many ways to generate microwave signals with optical technologies. The simplest one is called optical heterodyning. Suppose there are two optical waves whose frequencies, phases and powers are ω_1, ω_2, ϕ_1, ϕ_2, P_1 and P_2 respectively. If the two waves' frequencies approach and their polarization states are the same, when they enter into a high-frequency photodetector for producing beats, the output current is:

$$I=R[P_1+P_2+2\sqrt{P_1P_2}\cos((\omega_1-\omega_2)t+\phi_1-\phi_2)] \quad (1)$$

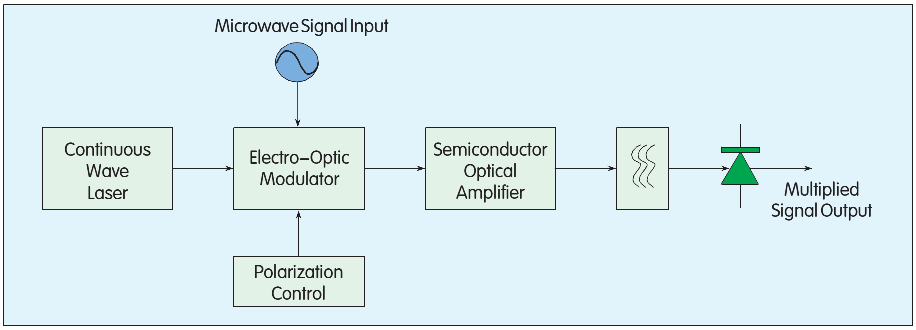
where R is the Optical/Electrical (O/E) conversion coefficient of the photodetector. It can be easily seen that by means of beating, microwave signal at the frequency of $|\omega_1-\omega_2|$ can be generated, and the signal's frequency and phase are not only determined by the frequency difference of the two waves, but also related to their phase difference. To ensure low phase noise and stability of generated microwave signals, the two waves should be highly coherent. Recently, many new methods have been reported to eliminate laser-induced phase noises, including optical injection locking[3] and optical phase-lock loop[4]. The optical injection locking method can only be used to lock

This work was supported by the National Natural Science Foundation of China under Grant No. 60736002 and No. 60807026.

a small range, often several MHz, while the optical phase-lock loop method requires the slave laser to keep up with phase change of the master laser, which means very small loop delay. Hence, both methods need stable external microwave signal sources, which leads to cost increase and hinders their application and productization.

One better solution is to integrate the two lasers (master and slave) into one with integration technique to allow the two waves to be generated in the same gain medium. Consequently, the two waves are highly coherent, and locking technology is avoided. In 1995, David Wake of British Telecom Research Institute first succeeded to output 42 GHz signal by beating with two longitudinal modes of a multi-longitudinal-mode Distributed Feedback (DFB) laser. Recently, dual-wavelength optical laser technology has also been developed. The optical laser is compact, handy as well as low-cost. The gain medium used in common optical lasers is erbium-doped fiber, which is featured in homogeneous broadening. To suppress the mode contention arisen from homogeneous broadening, dual-wavelength optical laser was developed, which can be used to generate microwave signals of 3-60 GHz. Methods for suppressing homogeneous broadening include low temperature[5], distributed dispersion cavity, polarization hole burning, spatial hole burning and spatially separated resonant cavities-based dual-wavelength DFB fiber laser[6].

Another optical generation method of microwave signals is external modulation technology[7], shown in Figure 1. The external modulator can be an intensity or phase modulator. In case of linear modulation, signals with a frequency two times over modulation frequency can be generated; and in case of deep modulation, microwave signals whose frequencies are four times over modulation frequencies can be generated. The advantage of external modulation technology is that the frequency is tunable by changing the frequencies of microwave modulation signals. Unlike in optical heterodyning, the stability and phase noise of



▲Figure 1. Experimental devices for external modulation method.

microwave signals generated with this method depend on both microwave modulation signals and modulator, so low requirements are imposed on the devices. In 2005, Canadian Yao Jianping Research Group proposed to use large microwave input powers to drive a Lithium Niobate (LiNbO3) modulator and then use a fiber grating filter to remove optical carrier components to obtain two optical sidebands. After beating with the two sidebands, tunable 32-50 GHz millimeter-wave signals can be obtained. In China, there are also many related reports. One example is combining sextuple-frequency multiplication of non-linear optical devices to generate microwave signals of 6-60 GHz[8].

As high-frequency electrical devices develop, there are microwave source modules under 60 GHz already sold in the market. To present their advantages, the optical generation methods should generate higher frequency microwave signals. Currently, the reported maximum frequency of output signals is 1,000 GHz at 25 μW[9], which indicates the coming of Terahertz (THz) era. Moreover, it is still attractive to use the gain saturation and recovery characteristics, optical polarization modulation, dispersion effect of Semiconductor Optical Amplifier (SOA) to generate and transmit Ultra-Wideband (UWB) pulse signals in the optical domain because the SOA can provide Ultra-Wideband over Fiber (UWBoF) communication systems with UWB pulse sources that are quite compatible with fiber systems[10].

1.2 Optical Modulator

Using fibers to transmit microwave subcarrier signals has raised new modulation demands on optical modulators. Direct modulation technique is simple, directly uploading microwave subcarrier signals onto optical waves by changing the injection current of the semiconductor laser. But the bandwidth in direct modulation is restrained by the resonant frequency of the laser. One way to reduce the threshold current of semiconductor laser, increase differential gain and bandwidth is the adoption of quantum structure. To further increase the bandwidth, it is required to reduce photon life and gain compression coefficient. However, due to the limit of gain compression coefficient, direct modulation bandwidth rarely exceeds 30 GHz in room temperature.

To modulate microwave signals of 60 GHz or higher frequency onto optical carriers, external modulation technology has to be used. The LiNbO3 modulator, which is traveling-wave structure, can modulate signals of 70 GHz bandwidth[11]. The electric-absorption modulator can also be used. Small and with low drive voltage, this modulator can be easily integrated with a laser or an optical detector, so it has a promising optical modulation device.

As to modulation technologies, there are other alternatives, for example, frequency up-conversion and heterodyning. In frequency up-conversion method, low-frequency microwave signals are modulated onto optical carriers for transmission, and they are up-converted into high frequency signals at the Base Station (BS). Although this method does not require high-performance optical modulator, it makes the BS more complicated. In heterodyning method, two ways of optical signals which are of certain frequency difference are transmitted and baseband signals are modulated; then at the BS, the two optical waves are beaten to generate microwave signals. This method suffers from dispersion effect of optical fiber.

1.3 Photodetector

The performance of optical detectors used in microwave photonics must excel those in regular optical communication systems in the following three aspects: High rate; large power output, which means high saturation working point; and capability of directly converting the signals into microwave power for transmission via microwave antenna. Currently, only Uni-Travelling-Carrier Photodiode (UTC-PD) meets the above requirements. In UTC-PD, only electrons are used as activated carriers and the cavity is limited in a certain region. It takes advantage of high mobility of electrons to greatly improve its response speed; adopts waveguide structure to extend the operation range of light absorption; and designs the optimal transmission impedance to achieve high response speed and high saturation power. It is reported that this device can be used to detect 1.5 THz signals at 1.55 μm band and it has been integrated with transmit antenna or a modulator to become a single-chip integrated device.

1.4 Microwave Photonic Filter

Microwave photonic filter makes an important part of photonic signal processing technology. In electronic domain, limited by frequency band and sampling frequency, the speed and precision of signal processing are affected. These limitations are called electronic bottlenecks. Microwave photonic filter provides a new approach to solve these bottlenecks: Input Radio Frequency (RF) signals are first modulated by a modulator onto optical signals; then they are processed in optical domain; finally, filtered microwave signals are output by an optical receiver. The advantages of this approach are: Low loss, high bandwidth, immunity to EMI, light weight and supporting high sampling frequency. Besides, the adoption of WDM technology makes it possible to concurrently process signals in space and wavelength.

Microwave photonic filter was originally applied in the radar system and aerospace field that require high-speed signal processing. As the research on RoF system advances, it has been applied in communication systems, particularly millimeter-wave RoF systems. Current research on the filter focuses on designing new structure to achieve frequency response with higher Q value, negative tap coefficient, tunability, reconfigurability and larger dynamic range. Traditionally, two structures are adopted. The first one is called electric differentiation structure, which was first implemented in 1995. But this structure performs poor in terms of tunability and reconfigurability and is restricted by bandwidths of electric devices. The second structure adopts complicated optoelectronic device to achieve full-coefficient filter. The cost of this structure is very high. Recently, many new, low-cost structures have been reported to realize microwave photonic filters with negative coefficients. Among them, the structures using polarization states and external modulators are the most attractive[12]. In RoF system, the combination of microwave photonic filtering function with other signal processing functions can dramatically reduce system cost and let functions centralize.

1.5 Analogue to Digital Converter

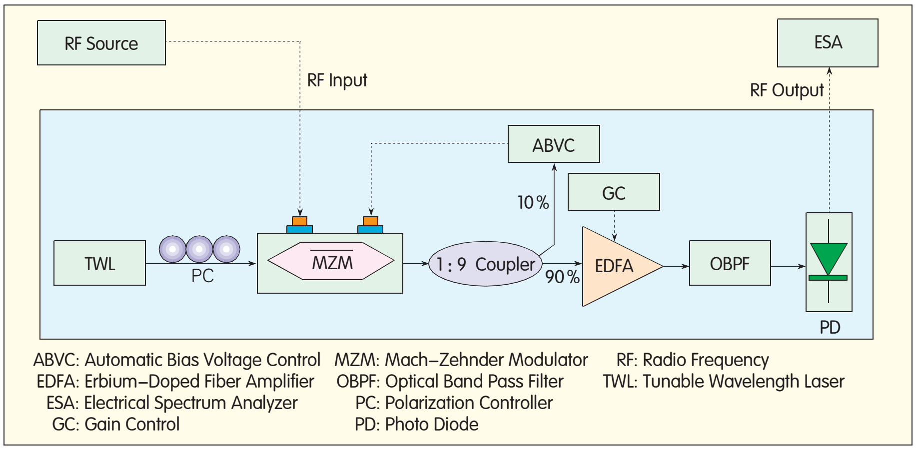
In some analog systems, such as radar or broadband communication system, the use of digital signal processing provides better performance and fast system reconfigurability. In electronic domain, the disadvantages of Analogue to Digital Converter (ADC) become more evident with frequencies going up because Complementary Metal Oxide Semiconductor (CMOS) digital converter is affected by such factors as sampling clock jitter, stable circuit hold time of sample, and comparator's processing speed. In digital signal processing, it is difficult to realize an ADC for 100 GHz sample. Time stretch, a photonic solution, enables ADC for 480 GHz sample within an intrinsic bandwidth of 96 GHz[13]. The basic principle of this technique is to slow down the electrical signal using photonic preprocessing to improve the performance of electronic ADC. The photonic time-stretch processing consists of three steps: Time-to-wavelength transformation, wavelength domain processing and wavelength-to-time mapping. The slow electrical signals after transformation can be converted with a common A/D converter.

1.6 Optical Domain-Based Microwave Amplifier

The gain of common EDFA and the optical-microwave interaction can be used to achieve microwave signal amplification in the optical domain, as shown in Figure 2. The Direct Current (DC) light output by an external cavity laser is modulated by the input microwave signals in Mach-Zehnder intensity modulator, with the DC bias point of the modulator remaining at about half-wave voltage. Then Erbium-Doped Fiber Amplifier (EDFA) amplifies the output optical signals and the Optical Band Pass Filter (OBPF) removes Amplified Spontaneous Emission (ASE) noises. Finally, the signals are input into a photoreceiver and restored into amplified microwave signals. Experiment results show that when microwave frequencies are kept at 4 GHz, microwave gains always remain about 17 dB even if the input microwave signals are amplified, which means good stability. Besides, Signal-to-Noise Ratios (SNRs) of output microwave signals increase accordingly.

1.7 Overcoming Effect of Microwave Subcarriers on Fiber Transmission Link

The transmission characteristics of microwave signals over the fiber are an important subject in the research of microwave photonics. Early when the Hybrid Fiber-Coaxial (HFC) system was used to transmitting analog Cable Television (CATV) signals, the link's transmission characteristics were a focus. Now related theoretical models have been used to analyzing the transmission characteristics of RoF links. On RoF links which are faster than CATV links, dispersion effect of fiber has become a main factor that limits transmission distance. Polarization-Mode Dispersion (PMD) and other nonlinearity effects are more evidently seen. As to chromatic dispersion effect, it is generally thought this problem can be solved with Single



▲Figure 2. Structure of optical domain-based microwave amplifier.

Sideband (SSB) modulation technology in optical domain. The most direct method to obtain optical SSB signals is to use fiber grating filter. But the filter itself is likely to induce dispersion into the system. Studies show that nonlinearity of external modulators has seriously restricted the dynamic range of the entire microwave link. Nonlinearity effects, such as cross-phase modulation, arisen from a large transmission power will further deteriorate system performance[14]. Meanwhile, signals of different digital modulation schemes require different millimeter-wave fiber transmission links. As a result, one hot topic in recent research of microwave fiber transmission system is the characteristics of links used to transmit digital baseband signals and Intermediate Frequency (IF) signals that adopt different modulation schemes, such as Quadrature Phase-Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) or use Orthogonal Frequency Division Multiplexing (OFDM) technology.

2 System Application

The earliest system application of microwave photonics took place in the Deep Space Network (DSN) in Mojave Desert, north of Los Angels at the end of 1970s. DSN consists of several large dish antennas that are distributed in a few dozen kilometers. The diameter of the largest antenna reaches 70 m. A fiber transmission system is constructed between these antennas to transmit 1.420405752 GHz ultra-stable microwave reference signals. Synchronized at this frequency and with phased array concept introduced, all antennas function as a huge antenna, communicating with and tracing the spacecrafts in the outer space. In 1990s, the CATV system, which is based on HFC and microwave photonics technology, became a great commercial success.

In recent years, an important objective of microwave photonics applications is to use fiber to transmit microwave carrier signals in wireless communications, that is, RF transmission system over fiber. One example is RoF communication system. RoF combines the advantages of microwave and fiber communications, enabling microwave signals to be transmitted over the fiber at low loss. It can be used for signal transfer and allocation between the central office and each microcell antenna. The advantage of RoF system is that it can deploy complicated microwave processing units in the central office and leave only O/E conversion unit and microwave transmit antenna at the BS. In this way, the BS structure is dramatically simplified and the cost is decreased. This helps to improve frequency reuse and cell's density. Moreover, RoF technology is completely transparent to frequency and modulation schemes. When frequency or modulation scheme changes, it is only required to upgrade the central office, so upgrade of the entire wireless communication network becomes easy.

In 1997, D. Wake Group of British Telecom set up a 60 GHz RoF system. In such a system, both analog satellite TV signals and digital signals can be carried, and 60 GHz millimeter-wave signals are generated from optical beating between master and slave lasers. In 2006, Korean Sejong University constructed a 60 GHz RoF system which uses optical fiber to transmit IF signals but completes frequencies mixing at the remote stations so as to avoid dispersion effect of fiber links. Recently, Professor G. K. Chang of US Georgia Institute of Technology developed a 2.5 Gb/s 40 GHz WDM-RoF system by combining microwave photonics with WDM Passive Optical Network (PON) technology[15]. One remarkable feature of this system is that it has no IF signals, so the transmitted baseband signals will no longer be affected by IF. In terms of BS design, the PON architecture simplifies the BS. In RoF field, Japanese research institutes are quite powerful due to their advantages in the research and development of such new optical devices as high performance LiNbO3 modulator and UTC-PD. In 2007, Japanese NTT Corporation reported that they succeeded to transmit 10 Gb/s digital baseband signals without any error code in a 125 GHz RoF system. On the whole, RoF systems tend to be full-duplex, WDM-based, function integration, low cost and high rate. In China, research on RoF has made great progress in recent two years. For example, experiments on 60 GHz millimeter-wave wired-wireless hybrid optical transmission system have succeeded[16], 32 GHz RoF High Definition Television (HDTV) service transmission platform has been set up, and RoF system with photonics generated OFDM signals has been worked out[17].

The military application is also an important subject in the research of microwave photonics. Microwave photonics has demonstrated its advantages in such applications as phased array radar[18] and remote fiber system with radar antennas. For example, optical controlled microwave beam forming network makes use of optical real-time delay devices, combining the distributed structure of feeder network, to perform such processing as power allocation, phase shift and power synthesis for multichannel microwave signals, thus achieving spatially distributed control over microwave signals. Optically controlled wideband phased array radar has many advantages, including quick scanning speed, high resolution, powerful anti−interference capability, small size and light weight; so it is quite suitable for airborne or shipborne radar system. The application of phased array radar technology in communications is optically controlled intelligent antenna. Intelligent antenna is a multi−antenna technology, using an antenna array to form controllable beams that point to and trace the users at any time. The advantages of intelligent antenna include: Increase of communication capacity and rate; EMI mitigation; reduced transmit powers of both handsets and BSs; positioning performance; reduced multi−path fading, and access of more users or achieving higher data rate.

The research achievements of microwave photonics have also been widely applied in intelligent transportation systems, highway vehicle communication systems[19] and ultra−high speed train communication systems. Supporting quick handover management and dynamic bandwidth allocation, RoF−based vehicle communication systems are quite competitive in the fields of mobile communication and vehicle communication.

3 Conclusions

In the last 30 years, microwave photonics has made remarkable progress in terms of theories, devices, key technologies and system application. Some applications have already been put into commercial use[20]. Microwave and photonics are two important disciplines that advance information technologies. The combination of the two technologies will have profound influence on modern information technology.

As a new interdiscipline, microwave photonics has promising prospects. In addition to CATV, RoF communication and radar systems, it may be applied in many areas, including broadcasting, wireless multimedia services, high definition video streams, Gigabit local area networks, personal area networks, optical detection and measurement and radio astronomy. Besides, it is expected to be further developed in the fields of THz technologies, high−sensitive sensing and quantum key distribution.

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