New Optoelectronic Devices and Technologies for RoF

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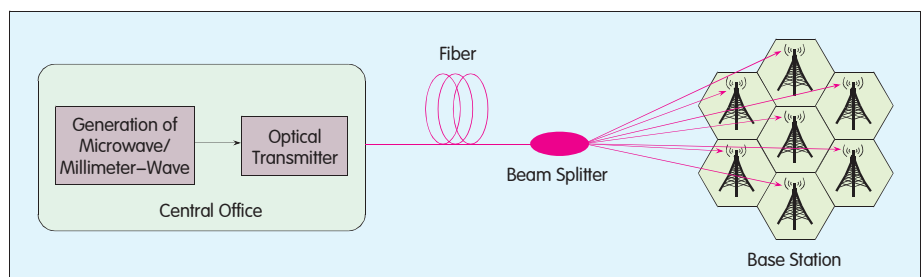
Abstract:

In the high-frequency microwave photonics field, Radio over Fiber (RoF) technology has become a hot topic in the development of next generation broadband wireless communication technologies. In recent years, based on new optoelectronic devices that support RoF technology, several optical generation and receiving techniques of millimeter-wave subcarriers have been developed, including external modulation, radio frequency up-conversion, heterodyning and millimeter-wave modulated optical pulse generator. The development of these technologies will no doubt quicken the pace of commercialization of RoF technology.

Microwave photonics is an interdiscipline that combines microwave technology and photonics technology, and its history can trace back to the invention of laser and fiber[1]. With maturity of ultra high-speed fiber communication technologies, popularization of broadband wireless personal mobile communication and increasing applications of microwave technologies in military, industry and frontier research, microwave photonics sees good development opportunities and promising prospects. Currently, fiber communication technologies are advanced enough to achieve high-speed broadband information transmission at 40 Gb/s on a single wavelength channel, and overcome dispersion and nonlinearity effects of fiber on optical devices; a breakthrough has been made in the research of obtaining higher frequency signals with optical time division multiplexing technology; and driven by optical technologies, Terahertz (THz) technology achieves a rapid progress. Meanwhile, in the field of high-frequency microwave photonics, Radio over Fiber (RoF) technology, which uses optical methods to generate millimeter-wave modulated subcarrier signals and integrates fiber transmission, high-speed optoelectronic devices and radiative transfer of millimeter-wave signals in the space, has become a hot topic in the next generation broadband wireless communication technologies. Figure 1 illustrates the basic structure of a RoF communication system.
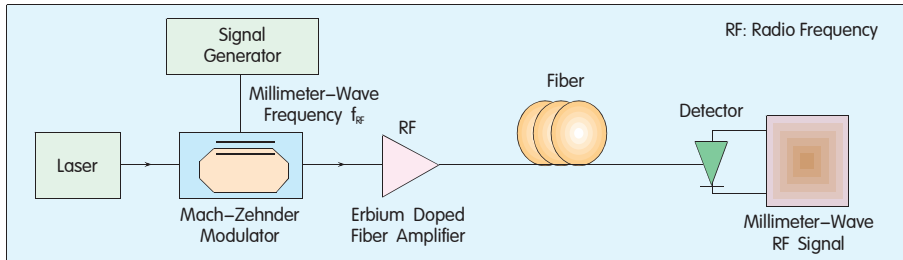
Generally, a RoF communication system consists of bidirectional transmitting/receiving module at the central office, transmitting/receiving module at the remote base station and fiber. Compared with traditional wireless communication systems, RoF communication systems cover wider ranges, have more bandwidths, incur lower costs, consume fewer powers and are easier to deploy. As a result, it is highly valuable in many fields, including future communication and military. At the same time, driven by laser technologies and optical communication technologies, new optoelectronic devices have also been developed for RoF systems. These devices have many advantages in comparison with microwave devices, including small size, light weight, fast speed, high precision, high efficiency, low power consumption and low cost. If achievements in laser, optoelectronic devices and fiber technologies are integrated with microwave technologies, they can be complementary to one another and solve some key bottleneck problems that they cannot overcome separately. Perhaps, some "surprising" results can also be produced. Therefore, it is essential to understand the key devices and technologies that are

▲Figure 1. Basic structure of RoF communication system.

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▲ Figure 2. RoF transmitter with external modulator.

required for optical millimeter–wave subcarrier communication.

1 Optoelectronic Device Based on Optical Generation Techniques of Millimeter–Wave Subcarrier Signals

As a millimeter–wave subcarrier operates at a high frequencies, it is very difficult to obtain it from direct modulation of a laser. The optical generation techniques of millimeter–wave signals proposed in recent years can be divided into four types[2]. The first one is external modulation, where high–speed external optical modulators, such as LiNO3 modulator, are used to modulate a high millimeter–wave frequency to light signal. The second type is frequency up–conversion technology, where frequency up–converters, such as audio–optical frequency shifter, are used to implement low–frequency microwave subcarriers' transmission over fiber and achieve frequency up–conversion at the Base Station (BS). The third one is heterodyning, where beating between lasers of special wavelengths and phase relationship are used at the detector. The fourth one is optical generation technologies based on some special photonic devices, such as superstructure fiber Bagg grating, Fabry–Perot (FP) resonant cavity and other optoelectronic devices.

1.1 External Modulation
External modulation[3–5] is the simplest and traditional optical generation method of millimeter–wave subcarriers and the main functional part used in this method is a high–speed optical modulator. The principle of the method is as follows: The optical wave output by a laser goes

through a Mach–Zehnder Modulator (MZM), and in succession a millimeter–wave RF signal containing transmission message is directly uploaded by the MZM. Thus, the optical wave forms a dual sideband modulated optical signal, as shown in Figure 2. At the optical receiver, each sideband will beat with the central frequency to generate RF signals at required millimeter–wave frequency. However, when dual sideband modulated optical waves are transmitted over the fiber, different phases will be generated for different frequency components due to chromatic dispersion effect. Consequently, the two beaten RF signals have different phases, causing RF signal power to change periodically with transmission distance and carrier frequency. Therefore, such methods as single sideband modulation[6], dispersion compensation for fiber grating[7] and optical phase conjugation[8] are used to overcome this problem.

1.2 Low–Frequency Microwave Transmission and Frequency Up–Conversion at BS
This method[9] mainly uses a frequency shift device, i.e. frequency up–converter. To overcome signal fluctuation arisen from dispersion effect, one feasible method is to transmit low–frequency subcarriers over the fiber and use a frequency up–converter at the BS to perform up–conversion so as to achieve high–frequency millimeter–wave carriers. At the transmitter end, low–frequency RF subcarriers are modulated onto optical waves by means of electro–optic modulation, and then sent to the receiver via the fiber. At the receiver end, the received signals are restored into low–frequency RF signals by way of Optical/Electrical (O/E) conversion, up–converted onto

millimeter–wave band and sent to the users via antennas. As the subcarrier frequency transmitted over the fiber is quite low, the influence of dispersion effect is very small. Moreover, the transmitter end does not require complicated and special light sources, but at the BS, a frequency up–converter and related millimeter–wave circuit equipment have to be added, which also increases the complexity and cost of the BS.
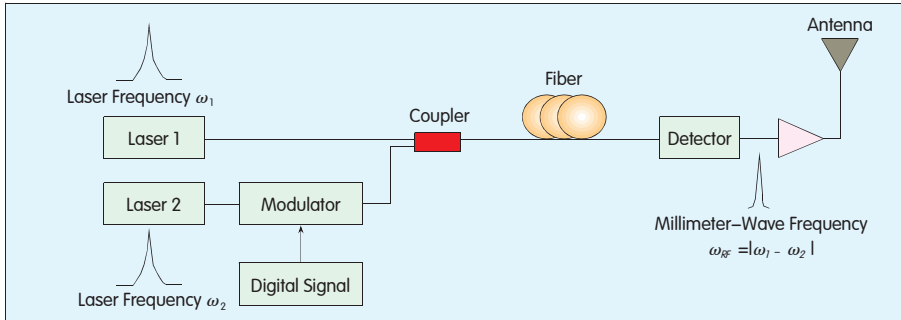
1.3 Heterodyning
Heterodyning[10] is the most common optical generation technology of millimeter–wave signals. Its performance depends on two phase–locked narrow linewidth lasers whose frequency difference is equal to required millimeter–wave frequency. One of the lasers carries baseband data with transmission information, which generates millimeter–wave carrier signals at BS using heterodyne method. Since the spectrums of two optical waves on the transmission fiber are very narrow, the dispersion effect is very small. As a result, heterodyning method can not only overcome fiber's dispersion effect, but also simplify BS structure and reduce the cost. It has been a hot topic in recent research of RoF transmitter. Moreover, because signals are directly modulated onto a narrow linewidth optical wave, it will not suffer the difficulty occurred in the high–frequency modulation and will prevent dispersion effect of fiber on high frequency modulated optical signals. Figure 3 illustrates the basic schematic diagram of this method.
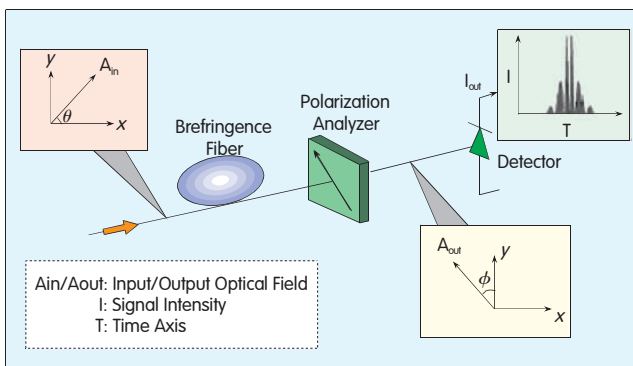
With two semiconductor lasers being used, phase noises may be produced, so do beaten millimeter–wave signals. Phase noises greatly influence system performance and they have to be eliminated. Several approaches have been worked out, including Optical Injection Locking (OIL)[11], Optical Phase–Lock Loop (OPLL)[12] and Optical Injection Phase–Lock Loop (OIPLL)[13].

1.4 Optical Generation Techniques of Millimeter–Wave Subcarrier Pulse Signals Based on Special Functional Devices
In addition to the above–mentioned optical generation techniques of

▲Figure 3. Schematic diagram of heterodyning.

Ain/Aout: Input/Output Optical Field
I: Signal Intensity
T: Time Axis

◄Figure 4. Generation of optical millimeter–wave pulse signal.

continuous millimeter–wave subcarrier modulated signals, optical generation technologies of millimeter–wave subcarrier pulse signals based on special functional devices or combined devices have attracted the attention of researchers, and certain achievements have been made recently. The basic idea behind these technologies is to use dispersion and nonlinearity effects of fiber or optical devices to achieve self–beating within an optical pulse. This method can transform a single optical pulse into a millimeter–wave frequency modulated optical pulse, which is then converted into a high–frequency millimeter–wave pulse signal by means of high–speed O/E conversion and sent out via an antenna.

Reference [14] first introduced this optical generation technology as shown in Figure 4. The polarization direction of linearly polarized input optical wave and the slow axis (i.e. X) of birefringence fiber form an inclination of θ, and the polarization analyzer is placed in such a way that it forms an inclination of ϕ with the fast axis (i.e. Y). When the optical pulse is transmitted over a fiber, it has two polarization components. Meanwhile, due to the action of dispersion and nonlinear self–phase modulation, the

different frequency of light will shift. Hence, beating will be produced between the two components when they pass through the polarization analyzer. That is to say, high frequency modulation takes place within a pulse envelope. Such a high–frequency modulation can be a single RF frequency or chirped frequency modulation, which depends on the selected fiber, the optical pulse parameters and their control.

To lower the control requirements for the fiber and optical pulse parameters, a Mach–Zehnder Interferometer (MZI) was used to replace birefringence fiber[14]. In such an experiment, the optical laser outputs an optical wave which was in the 1,550 nm band, with a pulse width of 3 ps and at a repetition frequency of

250 MHz. This optical wave was then input via an optical circulator to a 10 cm chirped fiber grating with a chirp rate of 0.13 nm/cm. After reflected by the fiber grating, the pulse became 1,000 ps wide. One arm of the MZI was connected to a variable delayer and a polarization controller. In this way, in the second coupler of the interferometer, beating may be produced between the front edge and rear edge of chirped optical pulse, thus resulting in a RF modulated optical pulse, i.e., millimeter–wave pulse signal. Following the above idea, optical generation technologies based on some special passive functional device based have also been proposed. One example was to use an apodized Moiré fiber grating filter with dual–peak wavelength to generate millimeter–wave subcarrier signals[15]. Figure 5 is a schematic diagram of this structure. As shown in Figure 5, the narrow input pulse was input into the fiber grating via an optical circulator and reflected back to the optical circulator, and finally it was output via another port. The fiber grating was dual–peak wavelength structure. The input spectrum was modulated by the fiber grating into dual–peak wavelength. When the beam was received by a photodiode, beating took place between the two wavelengths, and the beam was then converted into a millimeter–wave pulse. This dual–peak wavelength fiber grating can be designed with reverse engineering. In this solution, the basic structure is a specially designed Moiré grating, which is mature in terms of both design and process. Figure 6 is refractive index distribution and refraction spectrum of an apodized Moiré fiber grating.

The simple, low–reflectivity cavity Fabry–Perot filter can also be used to
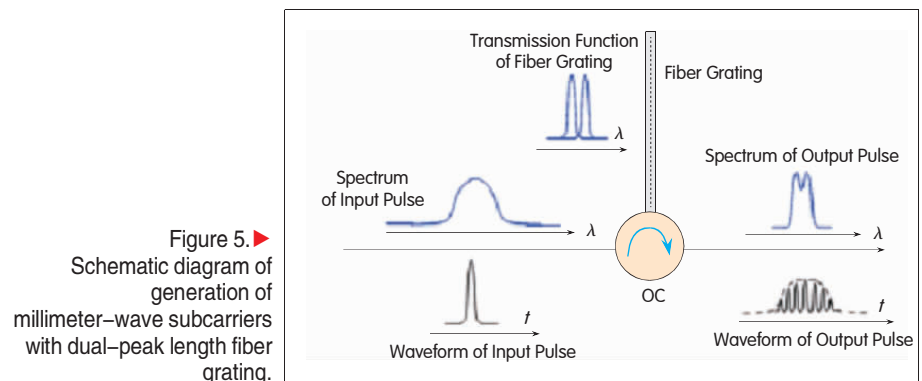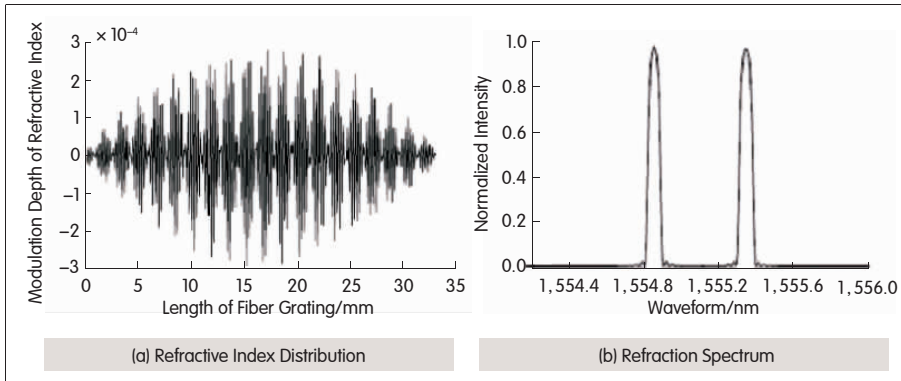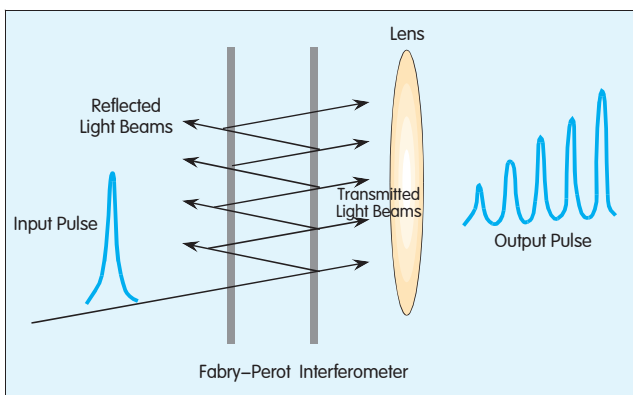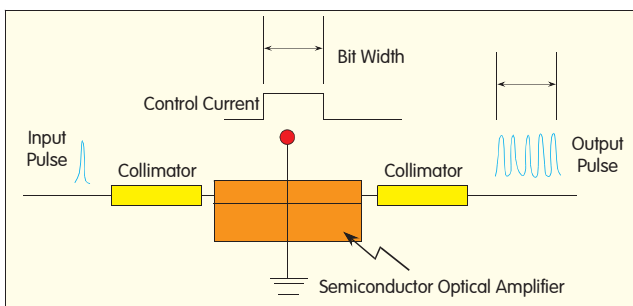

Figure 5.▶ Schematic diagram of generation of millimeter–wave subcarriers with dual–peak length fiber grating.

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▲Figure 6. Refractive index distribution and refraction spectrum of apodized Moiré fiber grating.

◄Figure 7. Generation of high repetition frequency pulse train with Fabry–Perot interferometer.

◄Figure 8. Generation and shaping of millimeter–wave optical pulse with SOA Fabry–Perot interferometer.

achieve optically generated millimeter–wave signals. This filter implements repeated delay of pulse to form ultra–short pulse trains at a high repetition frequency, i.e. millimeter–wave pulse envelope. The basic idea of this method is illustrated in Figure 7. Some initial theoretical analysis was given[16] to present the relationship between devices' characteristics and the microwave pulse characteristics. By adjusting the optical path and reflectivity of FP cavity, the repetition frequency, extinction ratio and envelope waveform can also be controlled. Research results show that this scheme is technically mature and simple to implement. To improve the quality and performance of

millimeter–wave pulse envelope, the FP can be used with Semiconductor Optical Amplifier (SOA). The basic idea of the method, shown in Figure 8, is to use the waveform of drive current pulse of SOA to generate the gain that is required by time–domain waveform so as to amplify and control optical pulse amplitude and

achieve shaping of pulse envelope. This method integrates the generation of pulse train at high repetition frequency and shaping of envelope waveform onto one device.
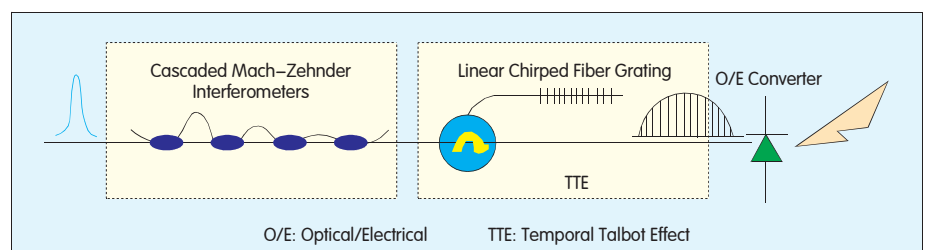
In addition, other new combined optoelectronic devices are used to generate millimeter–wave subcarriers. For example, Reference [17] proposed an optoelectronic device that integrates Pulse Repetition Rate Multiplication (PRRM) and Temporal Talbot Effect (TTE) (shown in Figure 9) and Reference [18] suggests cascaded Gires–Tournois Interferometer and ring resonant cavities (shown in Figure 10). The use of these new functional devices improves the millimeter–wave performance to some extent, promotes the development of RoF technology and enriches related technologies.
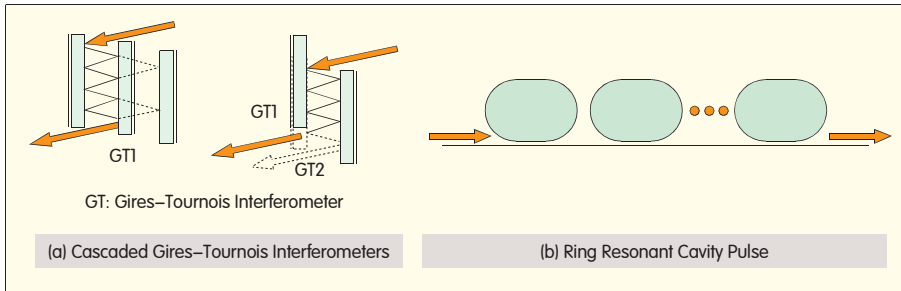
2 Reception Technologies in RoF

RoF receiving technologies also play a very critical role. In RoF systems, transmission and reception of optical carriers are done at the central office; while the BS is only configured with high–speed photodetector, modulator and antennas. The carriers from the central office, upon arriving at the BS via the fiber, are converted into electrical signals by a photodetector and sent out via antennas. On the other hand, the RF signals received by BS antennas are modulated by the modulator onto optical carriers and sent to the central office via the fiber. Having only photodetector, modulator and antennas, the BS's size is greatly decreased, and its cost is significantly reduced, thus promoting the development of dense "cells".
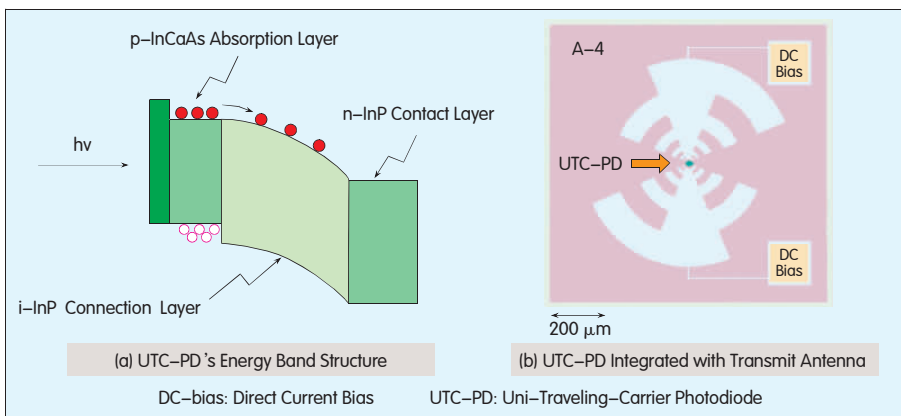
2.1 UTC–PD
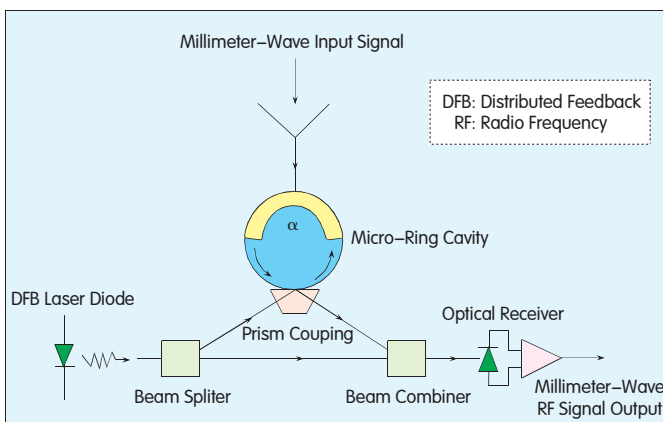According to RoF system configuration, the high–speed photodetector is an

▲Figure 9. Generation of millimeter–wave pulse with optoelectronic device combining PRRM and TTE.

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GT: Gires–Tournois Interferometer

(a) Cascaded Gires–Tournois Interferometers

(b) Ring Resonant Cavity Pulse

▲Figure 10. Generation of millimeter–wave pulse with cascaded Gires–Tournois interferometers or ring resonant cavity pulse.

(a) UTC–PD's Energy Band Structure

(b) UTC–PD Integrated with Transmit Antenna

DC–bias: Direct Current Bias   UTC–PD: Uni–Traveling–Carrier Photodiode

▲Figure 11. UTC–PD.

◄Figure 12. Schematic diagram of photonic microwave receiver.

important device at the receiving end of a fiber link. Compared with those used in regular optical communication systems, this detector must outperform them in the following aspects: High rate; large power output, which means high saturation working point; capability of directly converting the signals into microwave power for transmission via microwave antenna; and low price. Uni–Travelling Carrier Photodiode (UTC–PD) is such a device and it has already been launched. The basic principle of UTC–PD is to use electrons as activated carriers and limit

the cavity 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. The energy band structure of UTC–PD is shown in Figures 11(a), and 11(b) illustrates a device that integrates transmit antenna and UTC–PD[19]. According to Reference [20], UTC–PD's detection speed can reach 310 GHz, and

its output voltage at a 50 Ω load reaches 1.5 V (equivalent to an output power of 7.5 dBm). Moreover, RoF research results have proved its feasibility[21].

2.2 Photonic Microwave Receiver

Figure 12 shows a micro–cavity–based photonic microwave receiver[22]. As optical micro–cavity with high Q value is used, the resonance of light in the micro–cavity can greatly improve the system's modulation efficiency. Meanwhile, the metal diode used in the receiver is also microwave resonant structure, enabling RF signals to be amplified when they are coupled to the electrode. As a result, the defect of the structure proposed by Moodie et al is overcome: The structure can only be used to short–distance wireless communication due to large RF energy loss. Based on such a photonic microwave receiving structure, Levi et al succeeded in 100 M/s data transmission, and Ilchenko et al designed sub–microwatt photonic microwave receiver.

2.3 Electrooptic Modulator

Reference [22] also proposes an antenna–coupled electrooptic modulator. This modulator is originally designed for phase match between received RF signals and optical carriers. The electrode on the modulator acts as a receiving antenna. When an electromagnetic wave enters the modulator at a specified angle, phase difference between the signals received by adjacent antennas is exactly the phase change of the optical wave during it passing the antenna, thus achieving phase match.

3 Conclusion

Nowadays, RoF technology has become a research focus in the millimeter–wave field. It has widely been applied in wireless communication and radar systems, which are also one of important applications in microwave photonics. Much research has been done on the devices involved in microwave photonics, including light sources, modulators, transmission media, and detectors. The rapid development of new functional devices in microwave

photonics is a great drive for the application of RoF systems. According to related surveys and market development trends, the practical application of millimeter–wave RoF communication technologies in mobile communication and personal communication is subject to the competitiveness of new technologies in the economy, and largely depends on the breakthrough of related key devices and technologies as well. The progress in the research of these devices and technologies determines how quickly RoF technology is put into commercial use.

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Biography

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Qu Ronghui is the director and a doctoral advisor of the Laboratory for Information Optics of Shanghai Institute of Optics and Fine Mechanics (SIOM), Chinese Academy of Sciences (CAS). He is a member of China Institute of Communications and a member of Fiber Optics and Integrated Optics Committee of the Chinese Optical Society. His research interests include frontier technologies in optoelectronic development, research and development of new optoelectronic devices and related technologies. He has participated in the R&D of several important projects funded by the National Natural Science Foundation of China, the Ministry of Science and Technology of the People's Republic of China and CAS respectively. Up to now, he has published over 50 papers and applied for more than 10 patents.

Roundup

ZTE HSPA+ MIMO Solution Ready for Large Scale Commercialization

ZTE Corporation announced that it has completed the Inter–Operability Test（IOT）of its 3GPP R7–based HSPA+ MIMO solution, conducted in conjunction with mainstream terminal chip platform vendors, in July 2009.

ZTE's MIMO solution, realized with its SDR–based next–generation base station, has reached a theoretical speed limit of 28.8Mbps in both cable connection and wireless environment tests. The trials included data download services for UDP and FTP, as well as various IOT item tests. All the test results indicated stable and fast data download performance. The successful IOT testing confirms that ZTE's MIMO solution is now ready for large–scale commercial deployment worldwide.

"ZTE's HSPA+ MIMO solution shows our lead performance in the industry with its capacity for large–scale commericalization," said Zhang Jianguo, general manager for UMTS/LTE products, ZTE Corporation. "We look forward to collaborating with global operators to intruduce this state–of–the–art technology to fulfill market needs for next generation mobile communication."

ZTE has made numerous breakthroughs in the UMTS industry in recent years. It aims to drive innovative technology development with significant R&D investments in advanced HSPA+ and LTE technologies. ZTE's UMTS/HSPA+ commercial solutions have been widely adopted in more than 30 countries and regions around the world.　　**(ZTE Corporation)**

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