Ultra-Wideband RoF System and Its Key Technologies

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Abstract:
The microwave photonic technology-based Ultra-Wideband (UWB) Radio over Fiber (RoF) system is an important solution to the future low-cost and high-performance ultra-wideband wireless access network. Much research work has been done in this field with abundant results. This article introduces the RoF system that is based on the all-optical vector modulation technology to further enhance signal's spectrum efficiency; the full-duplex RoF system that is based on the millimeter wave Phase-Shift Keying (PSK) modulation to greatly simplify base station structure and fiber layout; and the RoF system that is based on multi-service mixed transmission to carry the service with both wired signal and several wireless signals. The article also presents an RoF-based high-definition video transmission platform.

The broadband access technology is drawing wide concerns as a solution to the growing demand for high-rate data, video and multimedia services. At present, the copper wire-based broadband access technology is reaching its highest possible application speed. Thanks to the research on Passive Optical Network (PON), the optical fiber has started to work for the access network to provide Gigabit access rate. Meanwhile, the broadband wireless access technologies are having their standards worked on or have already been deployed in commercial application due to their mobility and flexibility advantages. The industry is now expecting the integration of wireless and optical fiber networks as the evolution trend of the access network, to the ends of optimized resources and faster, more stable and flexible broadband access service. The concept of RoF is thereby proposed to provide dual broadband (fixed and mobile) service access on the fiber-based wireless access network. Besides the current microwave band, the millimeter wave (30-300 GHz) and UWB radio signals will help better tap the advantages and potentials of the RoF technology.

With the RoF technology, the Radio Frequency (RF) signals (millimeter wave included) are distributed through the optical fiber link between the Central Office (CO) and Base Station (BS). While simplifying structure of the remote BS, the RoF technology is also able to slash the cost of a whole broadband wireless access system with the help of centralized functions, shared devices and dynamically allocated spectrum broadband resource at the CO. The cost performance and bandwidth of a traditional wireless communication system are usually limited by the fact that most RF signals are processed by the electric signal processor in the BS. However, the configuration of centralized functions and optical-electric domain conversion of an RoF system make it possible for the CO to process all-optical RF signals. Such processing includes the all-optical vector modulation (such as QAM, DPSK and UWB signal) of optical generation of millimeter wave signals and complex codes, all-optical frequency conversion or mixing frequency, microwave photonic filter and spectrum crossing and multiplexing. The all-optical RF signal processing is better than traditional electric signal processing as it features higher bandwidth, lower loss, better anti-electromagnetic interference performance, higher sampling frequency and also the ability of parallel processing. The research of all-optical processing and fiber transmission technology for the UWB radio signals (millimeter wave signals included) is of paramount significance for the design and application of future low-cost, high-performance commercial UWB RoF access system. Breakthroughs concerning these key technologies will simplify the structure of remote BSs, cut cost of transmission and boost system's transmission performance, spectrum efficiency, coverage and flexibility, and above all, integrate the UWB millimeter wave wireless access and optical transmission technologies[1-10].

1 RoF System Based on All-Optical Vector Modulation Technology

It is very difficult to design and make the

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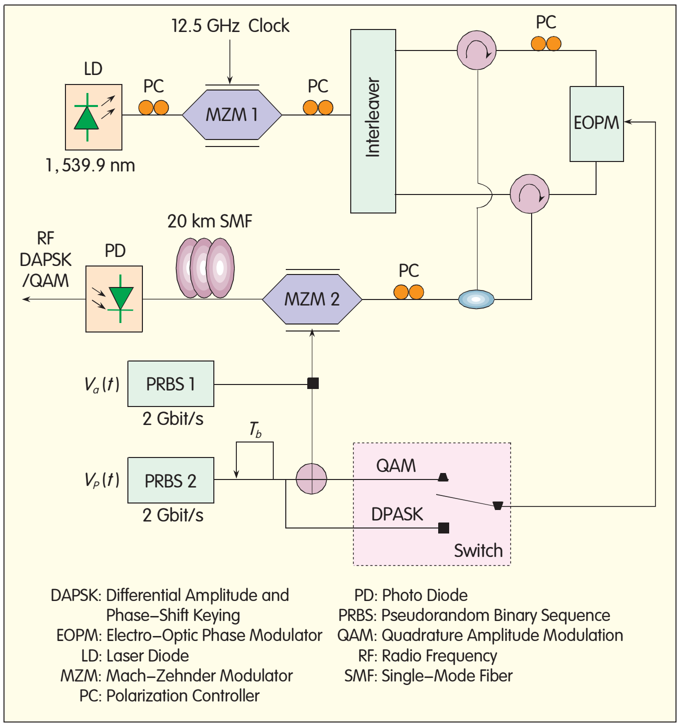


◀Figure 1. Block diagram of RoF system based on the all-optical vector DAPSK/QAM modulation technology.

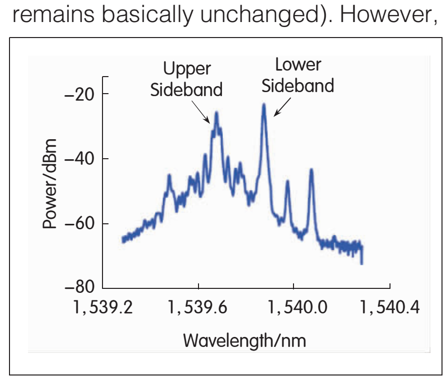
high-performance millimeter wave signal generator on the circuit, and even more difficult to perform various formats of high-speed digital modulation for the millimeter wave signals on the circuit. Therefore, it is of great importance to develop a device to perform high-speed digital vector signal modulation and demodulation for the optical millimeter wave signals. An all-optical vector Differential Amplitude and Phase-Shift Keying (DAPSK)/QAM modulation technology is proposed and employed it for the RoF system. As shown in Figure 1, firstly, the optical carrier modulates the RF clock through the Mach-Zehnder Modulator (MZM), which works in the totem-pole state at this point to perform carrier-suppressed double-sideband modulation. The comb filter separates the upper and lower side bands respectively after carrier suppression, so that the upper and lower side bands go through the Electro-Optic Phase Modulator (EOPM) in opposite directions. Due to the directional sensitivity of EOPM, the phase deviations of optical signals in different directions are not the same. As a result, the phase change of the upper side band that goes in forward direction is in direct proportion to the phase signal modulated on the EOPM; while the phase deviation of the lower side band that goes in reverse direction is in direct proportion to the average power of the electric signals modulated on the EOPM. After going through two optical circulators, the upper and lower side bands are coupled into one channel and then the amplitude signals are modulated. At the receiving end, the signals are beaten by the photo diode and then the DAPSK signals are obtained. If the voltage imposed on the EOPM is the sum of a certain percentage of phase signals plus amplitude signals, the round QAM signals are generated. To avoid dispersion, the phase signals need to undergo differential coding before they are transmitted through the optical fiber.

The phase signal in Figure 2 is a 2 GHz clock signal. As shown by the curve smoothness, the upper side band contains both phase and amplitude signals while the lower side band comes with the amplitude signals only.

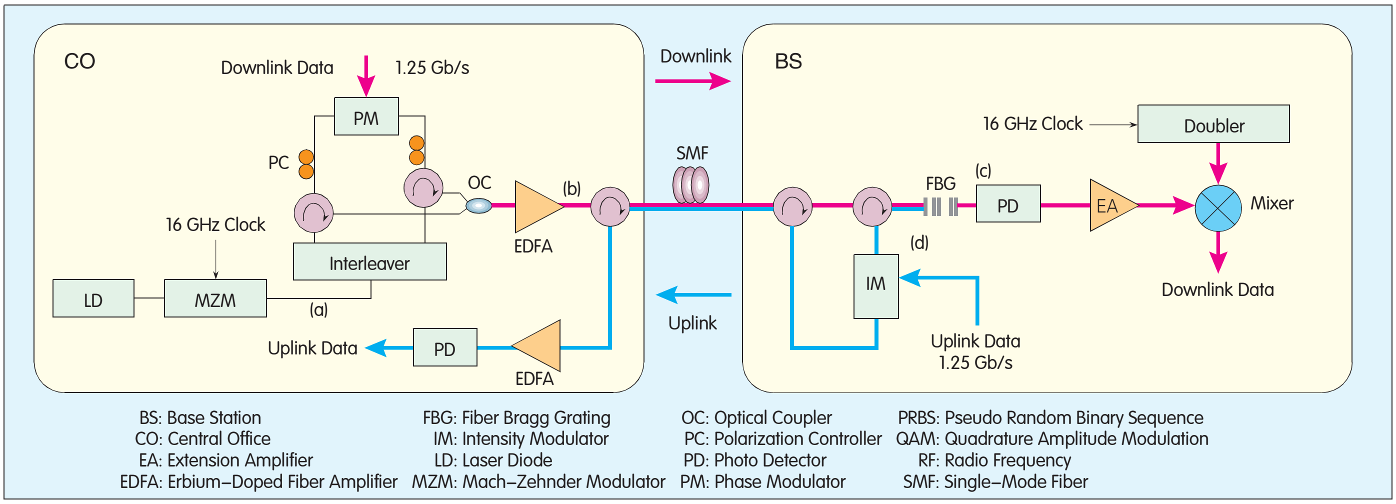
2 Full-Duplex RoF System Based on Millimeter PSK Modulation

Modulation pattern is one of the key technologies of the RoF system. The phase modulation signals generated directly by the EOPM need to be demodulated by a special device, for example, the Mach-Zehnder interferometer. A method of generating millimeter wave phase modulation is proposed in this article. As shown in Figure 3, the demodulation signals and amplitude modulation signals are exactly the same. The MZM bias realizes optical carrier suppression at the minimum transfer point to generate two side bands. The two side bands are then separated by the comb filter. Next, they go through the EOPM respectively in forward and reverse directions. Because of the different modulation efficiencies of the EOPM between forward and reverse directions, when the EOPM is imposed with external data signal modulation, different phase shifts are generated on the two side bands as the two go through the EOPM in opposite directions, and the difference between such phase shifts will be imposed with external data signal modulation. The two side bands are coupled for photoelectric conversion and then, the phase of the generated millimeter wave equals the phase difference between the two side bands, hence the millimeter wave signal of phase modulation.

Future access system is bound to be full duplex. Based on the method for generating millimeter wave phase modulation described before, a simple and reliable full duplex design is proposed here. The scheme is mainly based on optical grating of half reflection (a reflection index of 50%) and the full duplex operation of the passive base station goes in this way: Of the two side bands of the generated millimeter wave phase modulation signals, one has the same wavelength as the central wavelength of the half reflection optical grating, one has its transmitted spectrum decreased by 3 dB (the other one remains basically unchanged). However,



▲Figure 2. Optical spectrum of DPASK signal.



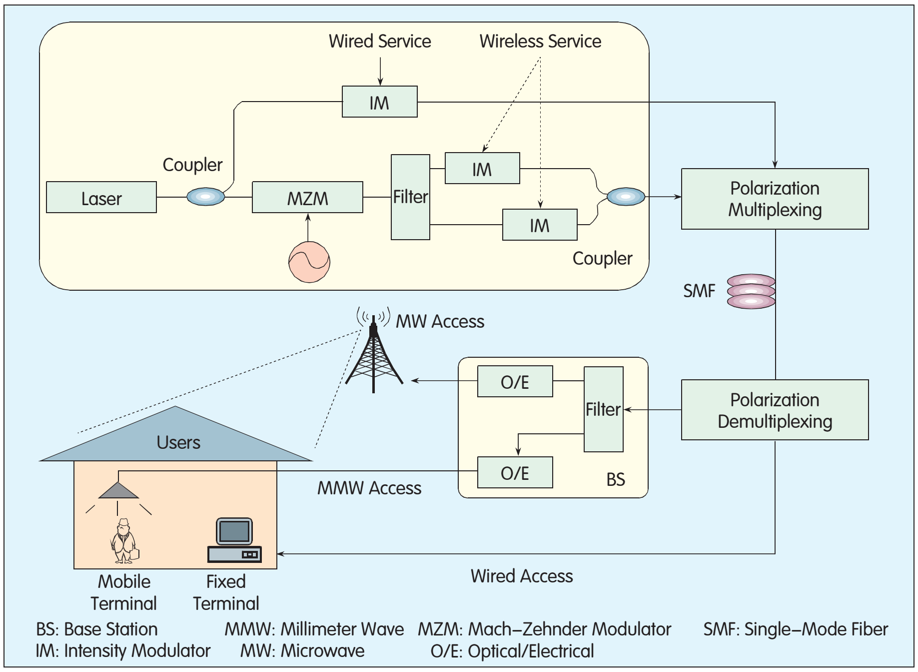
▲Figure 3. Block diagram of full-duplex RoF system based on millimeter wave PSK modulation.

the reflection spectrum, once isolated by the circulator, can work as the uplink signal optical carrier. The uplink data can finally be loaded with a low-insertion-loss intensity modulator.

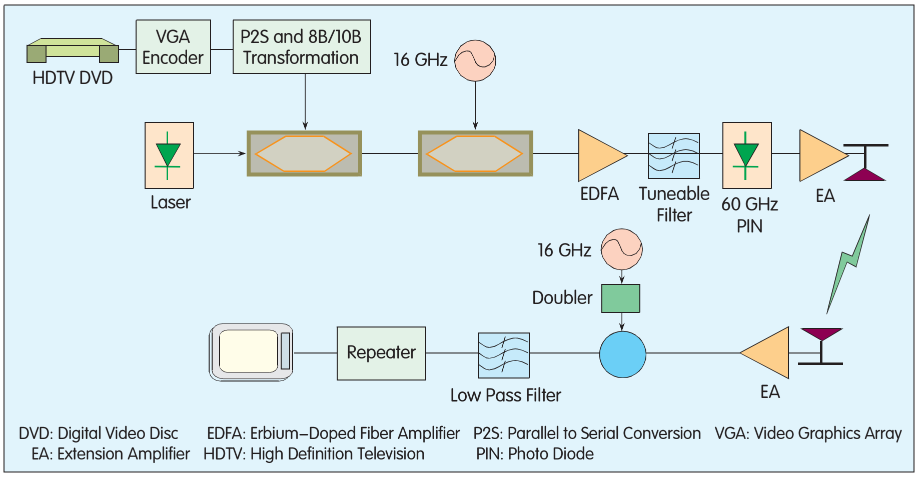
3 RoF System Based on Multi-Service Mixed Transmission

The millimeter wave RoF system is able to provide wireless access at a rate up to gigabit because of its high carrier frequency. This access technology is drawing wide interest as it features both transparent transmission of the optical broadband and the mobility and flexibility of the wireless communication. The future broadband access system, in view of the variety of user requirements and services, is expected to provide several access modes at the same time, including the fixed line access and broadband wireless access. This in turn requires that the RoF system is designed to carry multiple different services. Regarding this trend, This article proposes an RoF system that is able to transmit three different services at the same time through one optical fiber, including millimeter wave, microwave and wired access. Figure 4 is the block diagram of the system.

At the CO, on the one hand, the optical carrier provided by the optical generator is split into two parts. One part is loaded with the data signals that work as the optical carrier for wired access. The other part uses subcarrier modulation to carry the wireless service. Polarization directions of the two channels of signals are then tuned separately to be in the orthogonal state, next multiplexed in polarization-division multiplexing mode into one optical fiber for transmission. Because two orthogonal polarization states are transmitted independent of each other, they are separated at the user's receiving end to provide wired access and wireless access respectively. On the other hand, the optical carrier used to carry the wireless service undergoes up-conversion at the MZM. The MZM is set at the minimum transmission point to achieve optical carrier suppression and amplify the driven microwave signal to a proper value. With the nonlinearity of the modulator, the high-order side bands are generated. The side bands of fifth-order or higher can be ignored. The positive and negative first-order and third-order side bands are separated by the comb filter, with one optical channel containing only the positive and negative first-order side bands while the other containing only the positive and negative third-order side bands. In this way, the optical generation microwave and



▲Figure 4. Block diagram of RoF system based on multi-service mixed transmission.



▲Figure 5. Eye pattern of millimeter wave through different wireless transmission distances.

millimeter wave signals with the repetition frequency two and six times that of the local oscillation are produced. Such signals are respectively used to carry the access services at different rates, and then coupled into one optical fiber for transmission; finally they are separated by the comb filter at the base station. The optical generation millimeter wave with six times of frequency can be used to enable high-speed wireless service. However, due to the limited coverage of the millimeter wave as the wave attenuates in the air, the optical generation microwave with two times of frequency can be used to provide wireless services at a comparatively low speed, yet with a rather wide coverage, including the dead zone of the millimeter wave-enabled access.

At the base station, the three services need to be separated and sent to different users. First, the polarization beam splitter isolates the baseband signals that transmit the wired service and provides them to the fixed line users. Next, the comb filter separates the optical millimeter wave and microwave that carry the wireless services at two different frequency bands, and uses them for wireless access.

Features of the RoF System for multi-service mixed transmission are as follows:

(1) Low Cost

Cost can be slashed because only one optical modulator, instead of the microwave/millimeter wave generator, can produce microwaves of two times frequency and millimeter waves of six times frequency at the same time.

(2) High Spectrum Efficiency

The idle frequency bands at the gaps between millimeter wave side bands are made full use of, as three different services are transmitted in one optical fiber.

(3) Ability to Provide Multiple Services

Flexible access schemes can be designed to suit multiple services provided at the same time.

In the lab test of the scheme, the 5.8 GHz microwave drives the signals through the optical-electric modulator with a 10 GHz bandwidth and the optical comb filter with a 25/50 GHz bandwidth. The 11.2 GHz microwave signals and 34.8 GHz millimeter wave signals are then generated after all-optical processing. And then both optical and wireless transmissions are performed successfully for the 1.25 Gb/s high speed data over the 34.8 GHz millimeter wave. Specifically, the optical millimeter wave signals are transmitted through the optical fiber for 25 km at a power cost of less than 1.5 dB, while the millimeter wave signals are transmitted in the air for 2 m at a power cost of less than 2 dB.

4 High-Definition Television Service Transmission Platform

With the RoF system, whose wide transmission bandwidth is able to transmit the wireless data at up to 2.5 Gb/s, the uncompressed high-definition television can be transmitted through the optical fiber and accessed wirelessly. Figure 5 depicts a block diagram of the system. The domestic high-definition DVD source is used in the system. The RGB signals output by the Video Graphics Array (VGA) port are sampled to obtain the 1.1 Gb/s parallel signals. The parallel signals are encoded by a certain format, and converted synchronously from parallel to serial and from 8B to 10B, to generate the 1.3 Gb/s serial signals that are convenient for optical fiber transmission and clock recovery. The electric signals are amplified and then modulated to the level 1 MZM. The obtained optical signals go through the level MZM again and on the MZM, the 16 GHz RF carrier output by the microwave source undergoes frequency doubling on the light in the Carrier-Suppressed Return-to-Zero (CSRZ) format, thus having the 32 GHz optical carrier loaded. Next, detection is done in the electro-photonic detector and the output millimeter wave RF signals with the 32 GHz carrier are amplified by a 30 dB Ka band amplifier, before being transmitted by a pyramidal antenna driven for the transmission. The pyramidal antenna has a gain of 12 dBi. A same pyramidal antenna located at the receiving end receives the RF signals. The signals undergo low-noise amplification, frequency mixing and 、 low-pass filtering before restoring to the original high-definition television signals.

As some jitter and overlapping are produced while the signals go through modulation and wireless transmission several times, the signals are then regenerated and amplified regularly at a frequency-adaptable repeater. Next, the signals go through format conversion and serial-to-parallel conversion in an order reverse to the above described process and restore to the original RGB signals. Lab results indicate that the signals transmitted through the RoF link are stable and clear and basically the same as the high-definition television not transmitted through the optical link, with an error rate of below 10^{-12}.

Advantages and application prospects of the high-definition television service transmission system are as follows:

(1) The system adopts the unused communication frequency around

30 GHz millimeter wave instead of the low-end wireless frequency resource that is facing increasing pressure of use. The frequency it uses is suitable for short-distance signal transmission due to its high attenuation and it imposes little interference over the far-away common-frequency signals.

(2) The system features broadband for transmission. A 6-7 GHz bandwidth around 30 GHz is suitable for signal transmission. Owing to the large bandwidth for transmission, simple modulation will suffice and the system has the potential to transmit signals at higher rate. In the scheme proposed, the signals are transmitted at a rate up to 1.3 Gb/s. With the lab conditions, the signals can be transmitted and received smoothly at even 2.5 Gb/s.

(3) With the growing popularity of high-definition television, more and more video signals are collected following the high-definition standard. Our scheme will help transmit the video signals taken with the high-definition camera easily for processing. The high-definition television, and even future super high-definition television, can be played in household environment with great convenience and flexibility.

5 Conclusion

This article gives a brief introduction and analysis of the RoF system based on the all-optical vector modulation technology, the full-duplex RoF system based on the millimeter wave PSK modulation, the RoF system based on multi-service mixed transmission, and the RoF-based high-definition video transmission platform. The proposed scheme is able to simplify the structure of remote base stations, lower the cost for transmission and boost the system's transmission performance, spectrum efficiency, coverage rage, and flexibility. With such system the UWB millimeter wave wireless access and optical transmission technology are integrated and the technologies concerned will be translated to important solution to the future low-cost high-performance UWB wireless access network.

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Xu Kun is an associate professor and doctoral advisor at Beijing University of Posts and Telecommunications (BUPT). His research interests include optical fiber wireless integration system and networks, high-speed optical transmission and access technologies, microwave photon technology and all-optical information processing technology. He has published more than 70 papers, more than 40 of which are indexed by SCI, and he authored one book on RoF technology. His research work "UWB Microwave Photonic Signal Processing Technology and Application" is selected as one of the "Important Achievements of Photonic Technology in China 2008".

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