Optimization of Millimeter–Wave RoF System Structure

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Abstract:
Based on the seamless integration of broadband optical and wireless access networks, millimeter–wave Radio over Fiber (RoF) technology is considered to be a promising solution for the next generation access networks which will provide high capacity and flexibility with low cost. But due to its large cost to realize, the system architecture needs to be optimized. In the millimeter–wave optical generation part, optical heterodyning method can be introduced to generate a high–frequency millimeter–wave signal using a low–frequency signal source. And the system efficiency can be greatly improved based on injection–locking of a semiconductor laser. In the downlink, the transmission distance can be greatly enhanced using single–sideband modulation. And the single–mode modulation (single–sideband modulation) based on an injection–locked semiconductor laser is a much simpler solution. In the uplink, direct modulation of optical heterodyning signal can be used to realize the down–conversion of uplink millimeter–wave signal, which simplifies the receiver structure at the centre office. In the wavelength division multiplexing millimeter–wave RoF duplex system, the wavelength reuse in both downlink and uplink can save the wavelength resource in the whole system, which improves its efficiency.

A typical optical millimeter–wave Radio over Fiber (RoF) communication system mainly consists of three parts: Central Office (CO), Base Stations (BSs) and users. The CO and BSs are connected with fiber through which optical signals are transmitted; and optical millimeter–wave communication is adopted between BSs and users. The main functions of the CO include optical generation of downlink millimeter–wave signals, up–conversion of baseband signals, and receiving and processing of uplink signals; while the BS mainly performs Optical–to–Electrical (O/E) conversion, sends downlink signals, converts users' uplink electrical signals into optical signals and returns them back to the CO. As to optimization of optical millimeter–wave RoF system structure, the research currently focuses on uplink/downlink transmission of optical signals between the CO and BSs, specifically, optical generation of millimeter–wave signals, up–conversion of downlink signals, transmission performance, down–conversion of uplink signals and reuse of wavelengths on uplink/downlink.system.

1 Optimization of Millimeter–Wave Optical Generation Part

Traditional RoF communication systems usually use external RF sources to generate microwaves directly. But for optical millimeter–wave RoF systems, RF sources at millimeter–wave bands are quite expensive. If millimeter–wave signals can be generated with low–frequency RF sources or without any RF source, the system cost can be greatly reduced. Recently, the main method used for millimeter–wave optical generation is optical heterodyning. This method first uses low–frequency RF sources to generate a pair of optical coherent longitudinal–mode signals, whose mode space is the required millimeter–wave frequency. And then the generated signals are sent to a photodiode to beat millimeter–wave signals. The principle of this method is illustrated in Figure 1.

Optical heterodyne generation is mainly implemented with external modulators, which fall into two kinds by structure[1].

The first method is to use dual–arm Lithium Niobate ($LiNbO_3$) intensity modulator. It first selects a proper bias point to achieve carrier suppression modulation and then uses the two modulated first–order sidebands to achieve two coherent longitudinal modes. In this way, the frequency is doubled, and 60 GHz signals are generated from 30 GHz signal sources. The principle of this method is illustrated in Figure 2 (a).

The other method is to use a phase modulator and an optical notch filter. The notch filter is first used to filter optical carriers out from the output of the

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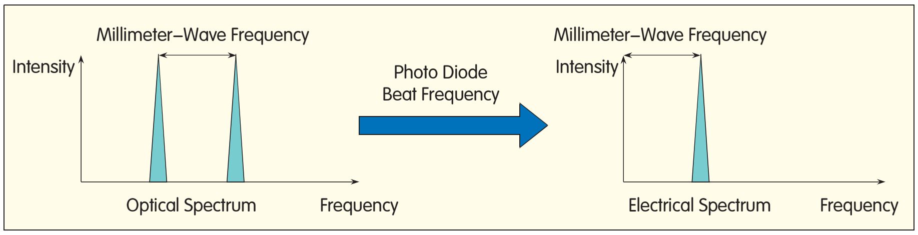


▲Figure 1. Principle of optical heterodyne generation.

modulator. Then the rest two first-order sidebands are used as optical coherent dual-longitudinal-mode signals. The principle of this method is shown in Figure 2 (b). Like the first one, this method also doubles the frequency, however, its structure is more complicate.

The above two optical generation methods generate 60 GHz signals out of 30 GHz signal sources. However, 30 GHz RF sources are still expensive. As a result, based on external modulation method, injection locking effect of some lasers is used to lower the frequencies of reference RF sources, allowing 60 GHz millimeter-wave signals to be generated from lower frequency sources.

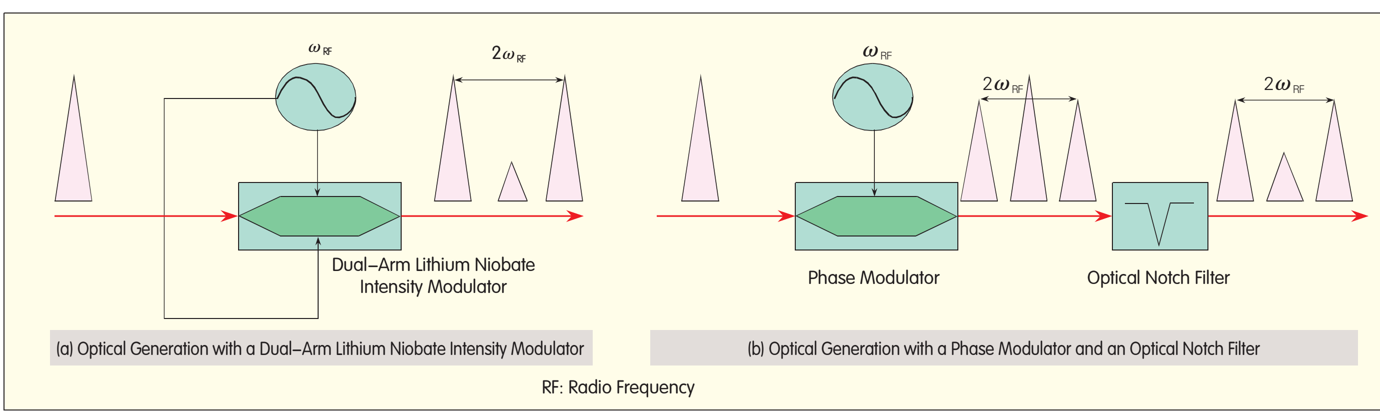
(1) Generation of 60 GHz Millimeter-Wave Signals based on Two-Mode Injection Locked FP Laser

Using two-mode injection locking effect of a Fabry-Perot (FP) laser can improve the quality of generated millimeter-wave signals and reduce phase noise[2]. By adjusting the modulator's bias point and FP laser's bias current, the second-order sideband injection locking effect of the laser can be realized, which enables 15 GHz RF sources to generate 60 GHz millimeter-wave signals[3]. The principle of this method is shown in Figure 3. The spectrums of optical coherent dual-longitudinal-mode signal and beaten electrical signal are shown in Figure 4.

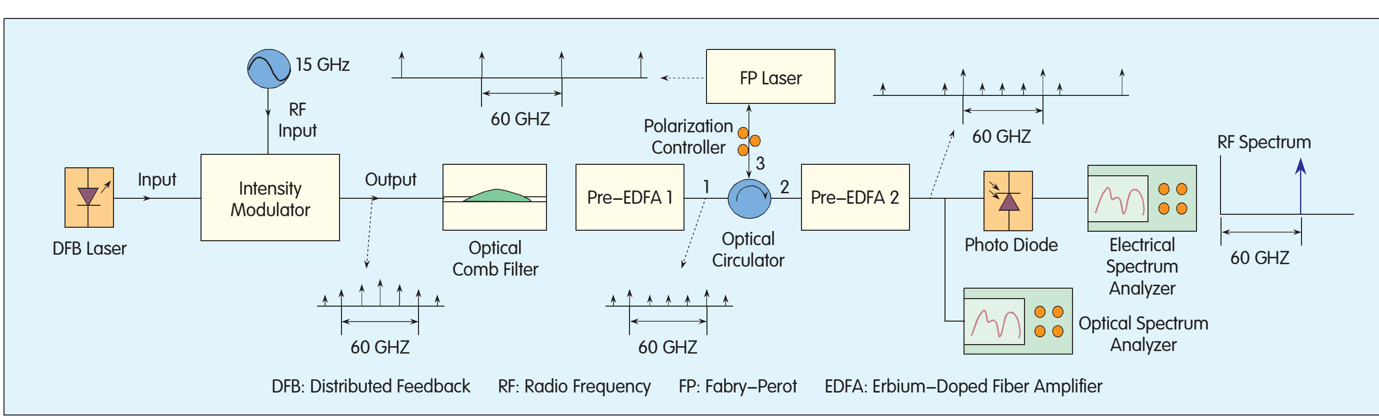
With FP laser's two-mode injection locking effect, the SNR of locked optical coherent dual-longitudinal-mode signals can be greater than 20 dB, and that of beaten electrical millimeter-wave signals is over 40 dB. At 100 kHz offset, phase noise is −94.30 dBc/Hz, which means good quality. Moreover, two-mode injection locking can also increase the direct modulation bandwidth of FP laser, as shown in Figure 5. This is very important in optical up-conversion of baseband signals and optical down-conversion of uplink signals, which we will discuss later.

(2) Generation of 60 GHz Millimeter-Wave Signals based on FWM Effect of Injection Locked DFB Laser

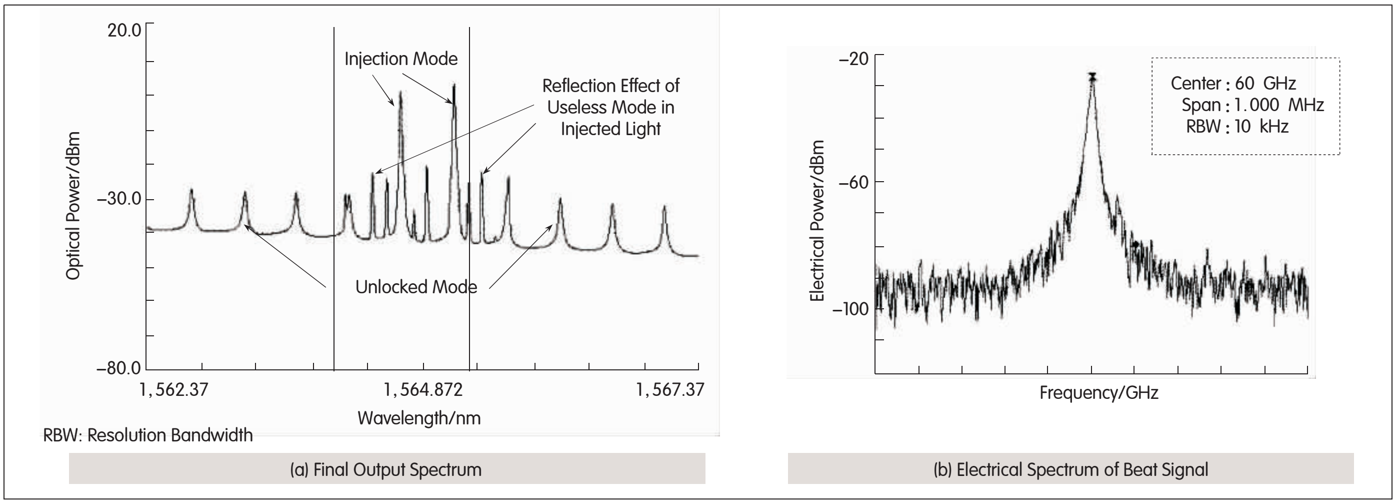
Four-Wave Mixing (FWM) effect is a kind of nonlinearity effect. Recently, it has been applied in highly nonlinear fiber and Semiconductor Optical Amplifier (SOA) to achieve multiplication of RF frequency[4-7]. Under the condition of



▲Figure 2. Optical heterodyne generation with external modulators.



▲Figure 3. Block diagram for 60 GHz millimeter-wave generation with two-mode injection locked FP laser.



▲Figure 4. Experiment results of 60 GHz millimeter-wave generation based on two-mode injection locked FP laser.

strong injection, FWM effect of injection locked Distribution Feedback (DFB) laser can be used to achieve tripling of frequencies, that is, to generate 60 GHz millimeter-wave signals from 20 GHz RF sources.

In this method, the direct or indirect modulated seed light is injected to enhance the locked mode by the way of injection locking. Figure 6 (a) gives the experiment principle diagram; Figure 6 (b) compares spectrums of input optical signal and output FWM signal of DFB laser. For the input signals, the power of second-order sideband signal is over 30 dB lower than that of first-order sideband signal, and no 60 GHz signals are directly beaten. While with FWM effect, the second-order sideband signal is amplified by 25 dB, and the long-wavelength first-order sideband signal that has been injection locked is also amplified. Figure 6 (c) shows the spectrum of beaten 60 GHz electrical signal. At 100 kHz offset, the phase noise of the signal is less than −95 dBc/Hz. Meanwhile, the signal quality is only 5 dB degradation compared with reference 20 GHz RF source, as shown in Figure 6 (d). Therefore, high quality millimeter-wave signals can be generated by the method.

Lower reference frequency sources, e.g. 10 GHz, are used to generate 60 GHz millimeter-wave signals, too. Experiment results show that the phase noise at 100 kHz offset is lower than −90 dBc/Hz, and there are only 10 dB's phase noise loss compared with reference sources.

2 Optimization of Optical Up-Conversion Structure and Transmission Performance of Downlink Baseband Signals

In traditional RoF systems, external RF sources are used, so a high-frequency mixer is necessary for performing up-conversion of downlink baseband signals, and the mixed microwave signals are then modulated onto optical carriers via an external modulator. In millimeter-wave RoF systems, since millimeter-wave sources are very expensive, optical heterodyne method has been adopted to generate millimeter-wave signals. Accordingly, the structure for baseband signals' up-conversion has to be changed.

In case external modulation methods have been used in the optical generation, one optical modulator can be added to perform up-conversion of baseband signals. While in case of two-mode injection locking with FP laser, up-conversion of baseband signals can be achieved with direct modulation of currents of FP laser.

In the above two up-conversion methods, dual-mode modulation of optical coherent dual-longitudinal-mode signals is finally achieved, which means both longitudinal modes are carried with baseband signals. However, in millimeter-wave RoF communication systems, the fiber chromatic dispersion effect (particularly at 1.55 um) limits the transmission distance of optical signals.

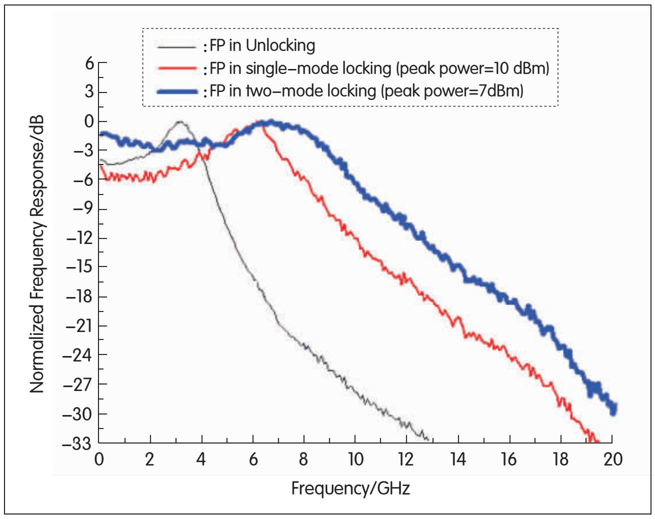
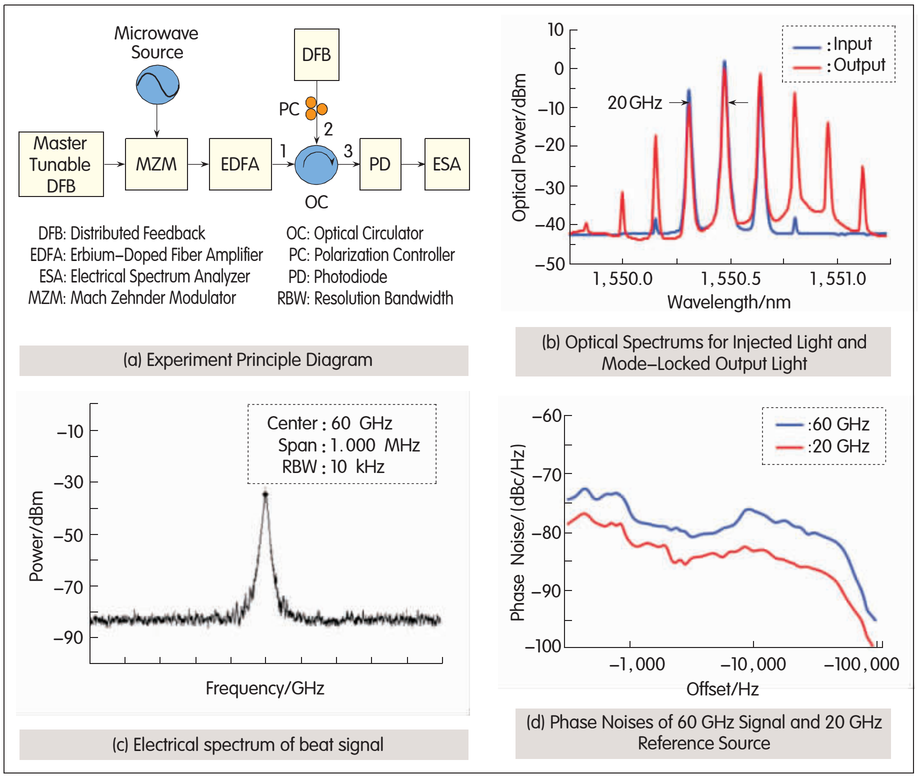


Figure 5.▶ Frequency responses in case of injection and non-injection with FP laser.



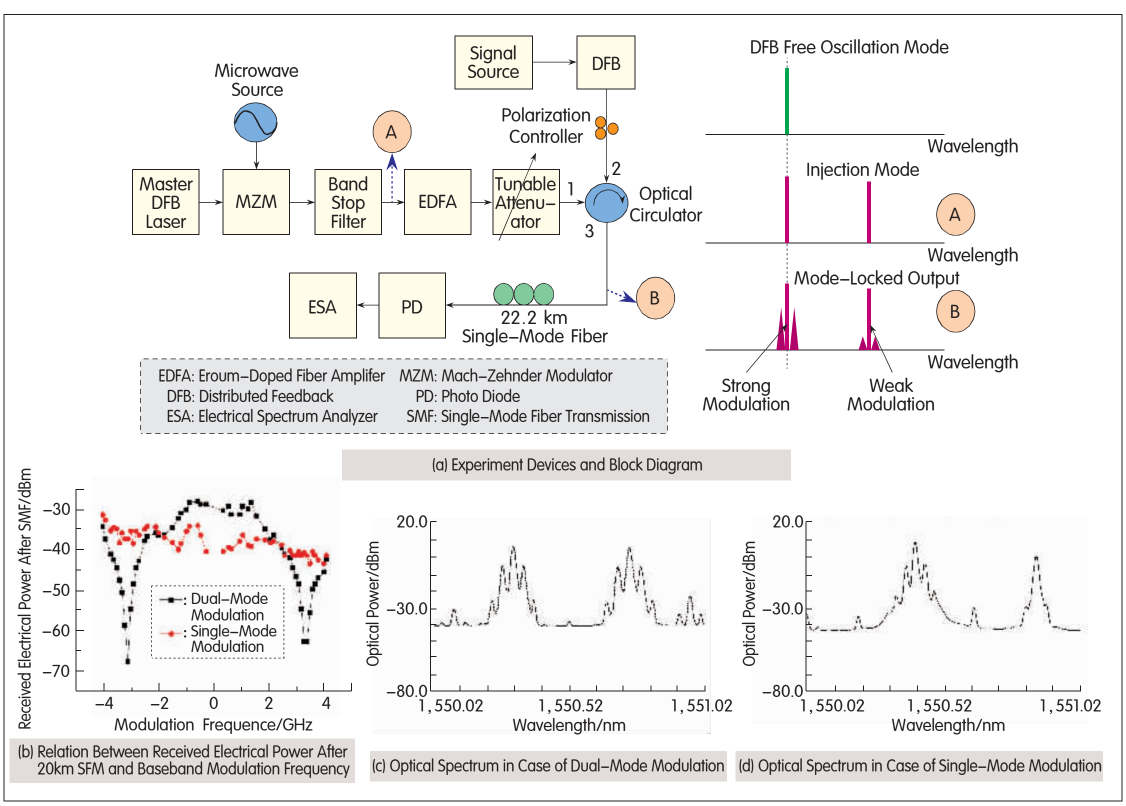
(a) Experiment Principle Diagram
(b) Optical Spectrums for Injected Light and Mode-Locked Output Light
(c) Electrical spectrum of beat signal
(d) Phase Noises of 60 GHz Signal and 20 GHz Reference Source

▲Figure 6. Generation of 60 GHz millimeter-wave signals based on FWM effect of DFB laser.

Compared with traditional Double Sideband (DSB) modulation, dual-mode modulation is better in suppressing chromatic dispersion effect of transmission, but it does not perform as well as traditional Single Sideband (SSB) modulation[8].

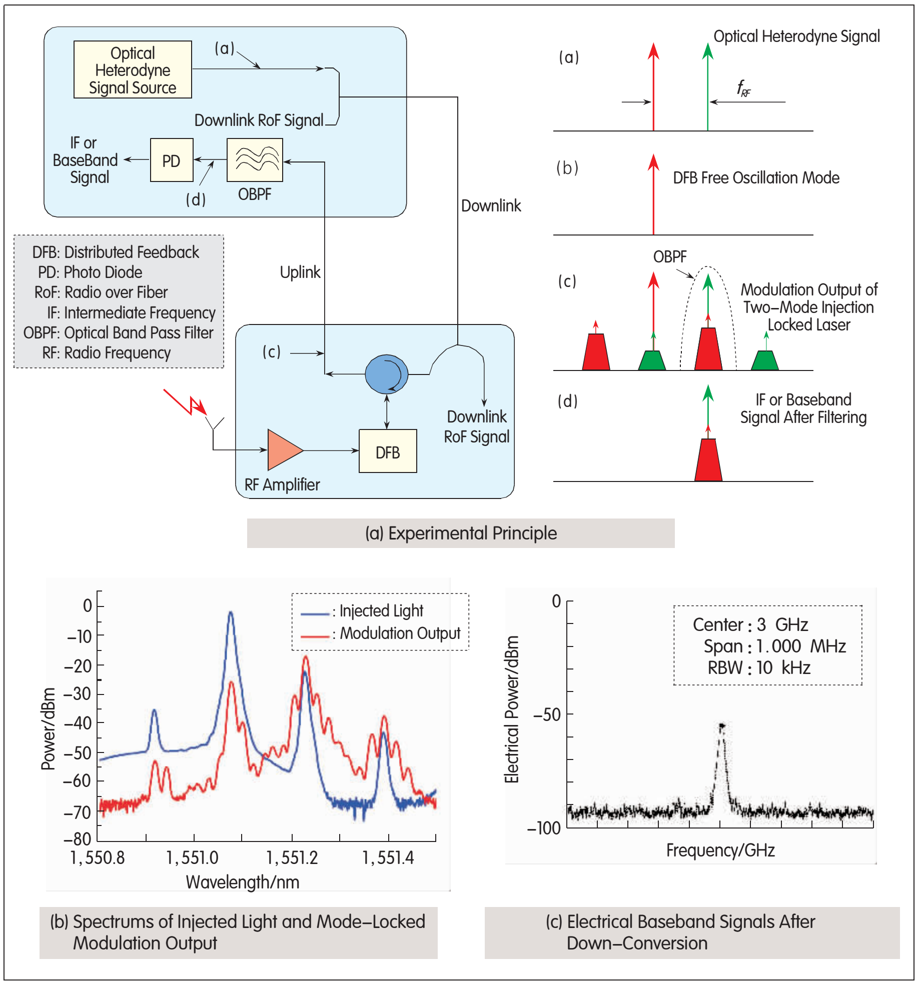
Recently, there are several methods of implementing high-frequency SSB modulation or single-longitudinal-mode modulation, including DSB modulation and filtering[9], independent modulation of one longitudinal mode after filtering out with optical heterodyning[10], and selective amplification function of strong injection locked DFB laser[11]. The method discussed in Reference [11] requires high direct modulation frequency response for DFB laser. Recently, a new single-mode modulation scheme, which is based on single-mode locking of DFB laser and is similar to SSB modulation, is proposed[12]. With this method, downlink baseband signals can be modulated onto the injection locked longitudinal mode of the two optical longitudinal modes, thus dispersion effect is considerably mitigated.

The experiment devices and block diagram of the above method are shown in Figure 7 (a). Figure 7 (b) illustrates how the power of a millimeter-wave signal, received after 22.2 km single-mode fiber transmission, changes with baseband modulation frequency (in the experiment, the center frequency is 54 GHz, and first-order sideband single-mode



(a) Experiment Devices and Block Diagram
(b) Relation Between Received Electrical Power After 20km SFM and Baseband Modulation Frequency
(c) Optical Spectrum in Case of Dual-Mode Modulation
(d) Optical Spectrum in Case of Single-Mode Modulation

◀Figure 7. Experiment of single-mode modulation with single-mode injection locked DFB laser.



▲Figure 8. Experiment of optical down-conversion based on injection locked DFB laser.

injection locking is adopted). From the figure, it can be seen that single-mode modulation is much more advantageous than dual-mode modulation in combating dispersion effect. In the dual-mode modulation, a deep RF power fading is found at the baseband frequency of 3 GHz, while in single-mode modulation, the powers remain relatively stable. Figure 7 (c) shows the optical spectrum output with dual-mode modulation, while in Figure 7 (d) the spectrum of baseband data is uploaded with one more modulator added in external modulation approach. From Figure 7 (c), we can see that when slave DFB laser's current changes, the modulation index of the injection locked mode (i.e. 1,550.39 nm) is relatively large due to injection locking effect, while that of the non-injection locked mode (i.e. 1,550.82 nm) is relatively small, and their difference exceeds 22 dB. Experiments have also been made on RoF single-mode modulation of 60 GHz millimeter-wave at a data transmission rate of 2.5 Gb/s, where G.652 single-mode fiber is used, and the transmission distance is 50 km. After transmission, the eye diagram is still very clear, which means error code-free transmission is achieved. In case of dual-mode modulation, the eye diagram cannot be obtained.

3 Optimization of Down-Conversion Structure of Uplink Signals

In traditional RoF systems, a common practice of converting microwave signals into baseband signals is to use a mixer at the BS or CO to complete down-conversion of the signals in electrical domain. But for millimeter-wave RoF systems, due to high expenses of millimeter-wave RF sources, the down-conversion structure of the system has to be optimized to save the cost.

One optimization approach is to adopt a high speed electro-absorption modulator at the BS[13]. This modulator is first used to modulate those optical coherent dual-longitudinal-mode signals which are idle and at a frequency interval of millimeter-wave frequency on the downlink; and then low-frequency baseband signals are directly detected. In this way, down-conversion of uplink signals is achieved.

Another feasible method is to implement optical down-conversion with an injection locked DFB laser. The experimental principle of this method is illustrated in Figure 8. Studies have proved that in case of strong injection locking, DFB laser or Vertical Cavity Surface Emitting Laser (VCOEL) can considerably improve its frequency response[14-15]. As analyzed above, dual-mode injection locking can also increase the frequency response of a semiconductor laser. In the experiments which we use an injection locked DFB laser to implement optical down-conversion, the DFB laser's direct modulation response can be increased from 5 GHz (free oscillation) to over 20 GHz (injection locking). If the optical coherent dual-longitudinal-mode signals whose mode-space is millimeter-wave frequency are sent from the CO to the BS and injection locked into the DFB laser, and at the same time, the antenna signals received by the BS are modulated onto the DFB laser. The sideband of the longitudinal mode with injected signals will fall into the baseband of another longitudinal mode after signal modulation. As the two longitudinal modes are coherent, intermediate-frequency or baseband signals can be obtained with direct optical filtering method. Therefore, down-conversion of millimeter-wave signals is achieved without any high-speed photodiode or mixer.

4 Wavelength Reuse in WDM Millimeter-Wave RoF System

In one-way RoF system (with one CO

and one BS), uplink and downlink can take different wavelengths respectively. But in actual applications, due to short operating ranges of millimeter-wave signals, many BSs have to be deployed. In this case, an important issue in designing WDM-RoF system is reducing the costs of BSs. In optical networks, wavelength is an important resource. Reuse of wavelengths can greatly reduce resource consumption. Therefore, current WDM Passive Optical Network (WDM-PON) has become a mainstream in the development of optical networks. At present, there are several solutions to implement WDM-PON in millimeter-wave RoF system.

(1) The CO sends downlink signals via external modulators but remains the optical carrier, and intensity modulation schemes are adopted for downlink baseband data. At the BS, the optical carrier is first filtered with an optical filter; and then the down-converted uplink baseband signals are modulated in optical domain with a modulator or SOA and transmitted as uplink signals.

(2) The CO uses external modulation method to generate heterodyne signals, and Differential Phase-Shift Keying (DPSK) modulation is adopted to upload downlink baseband data. At the BS, the downlink data are demodulated with a 1 bit Mach-Zehnder interferometer; while for uplink baseband data, they can be modulated in optical domain with a LiNbO3 modulator using intensity modulation scheme, and the CO just performs intensity detection of these signals.

5 Conclusion

Having huge advantages in transmission bandwidth and wireless access, millimeter-wave RoF system is a potentially promising solution for next generation access networks. Currently, the millimeter-wave devices are very expensive. To address the cost and resource issues, this paper discusses the optimization of millimeter-wave RoF system structure in terms of millimeter-wave optical generation, up-conversion of downlink signals, transmission performance, down-conversion of uplink signals and reuse of wavelengths on both uplink and downlink. With the research on its structure optimization fruiting, millimeter-wave RoF system is expected to be put into practice in the near future.

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