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REVIEW ARTICLE

Researches in microwave photonics based packages for millimeter wave system with wide bandwidth and large dynamic range

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Abstract This paper presents an introduction to the researches in microwave photonics based packages and its application, a 973 project (No. 2012CB315600), which focuses on addressing new requirements for millimeter wave (MMW) system to work with higher frequency, wider bandwidth, larger dynamic range and longer distance of signal distribution. Its key scientific problems, main research contents and objectives are briefed, and some latest achievements by the project team, including generation of linear frequency modulation wave (LFMW), tunable optoelectronic oscillator (OEO) with lower phase noise, reconfigurable filter with higher Q value, time delay line with wider frequency range, down conversion with gain, and local oscillator (LO) transmission with stable phase, are introduced briefly.

Keywords linear frequency modulation wave (LFMW) generation, tunable optoelectronic oscillator (OEO), reconfigurable filter, time delay line, down-conversion, phase stable transmission

1 Introduction

Millimeter wave (MMW) systems have been attracted a plenty of researchers for decades of years due to their applications in fields, such as remote sensing, deep space exploration, radar, communication, and so on [1]. Currently, such systems are being evolved, on different practical demands, in the direction of higher frequency, or wider bandwidth, or larger dynamic ranges, or longer distance of signal distribution, or all above [2–5]. For example, to increase the capacity of wireless communication system, more high frequency bands, such as 60, 120 GHz, etc., are discussed to be made the use of [2]; imaging radars see the trend to track in short time flying objects with high speed and get their images with better resolution by employing higher frequency and wider bandwidth [3]; and more and more distributed sensing structures are employed by either deep space probes or radars to obtain information of more remote heavenly bodies [4] or discover stealth objects [5].

MMW systems vary with different applications. 2012CB315600 project team put forward a simple model to describe MMW systems, as shown in Fig. 1. According to the model, the system contains transmitting and receiving terminals, and the transmitting terminal can be simplified to be made up with signal generation and beam forming network (BFN), while the receiving terminal with BFN, tunable and reconfigurable radio frequency (RF) filter, local oscillator (LO) and its phase stable transmission line, down-conversion mixer, transmission line, analog to digital converter (ADC) and digital signal processing.

The evolution of MMW systems post challenges on the realization of these packages: linear frequency modulation wave (LFMW) with high frequency and wide instantaneous bandwidth (IB) generated electronically offsets advantages from wide IB [6]; it is still a hard work to realize a high frequency LO with low phase noise [7], never mention to transmit it to a distant antenna with a stable phase; wide band true time delay [8] and reconfigurable filter with higher Q value are still in need [9].

To address those challenges, researchers began to investigate new principles. Among them, microwave photonics based scheme was thought a promising one. Microwave photonics make use of optical components to generate, transmit, manipulate, process wide bandwidth microwave signal. Generally speaking, microwave photo-

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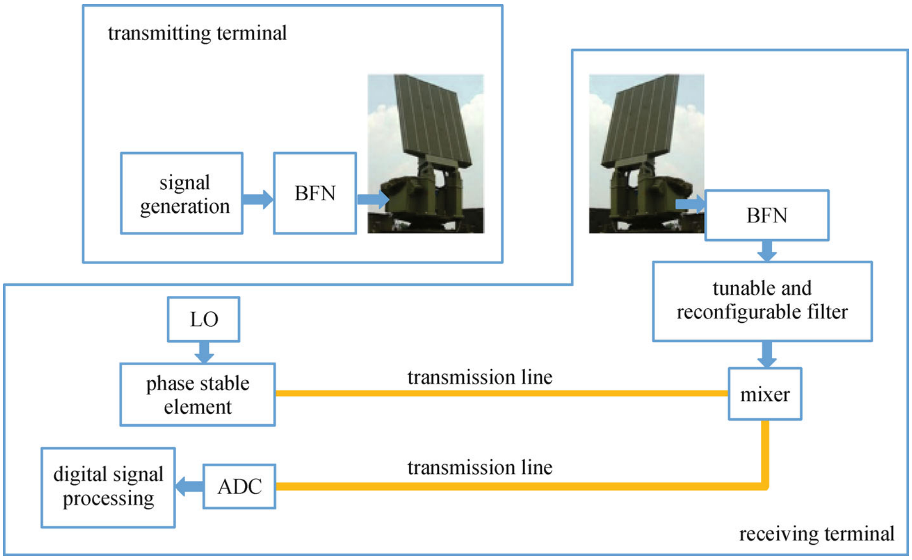


Fig. 1 A simplified model of millimeter wave (MMW) system. BFN: beam forming network; LO: local oscillator; ADC: analog to digital converter

nics, first up-converts MMW signal into light frequency, and then processes optical signal, finally down-converts into MMW. Due to the high frequency of around 200 THz, the laser has in 1550 nm band, those of wide bandwidth in electrical domain are of narrow bandwidth in optical domain, and the mature narrow bandwidth signal processing theory can be employed in optical domain to deal with wide bandwidth MMW signal. Also, optical components have bandwidth of more than 100 GHz, so that they have the ability to deal with ultra-bandwidth MMW which electronic components donot. Furthermore, fiber features a loss lower than 0.2 dB/km which is far less than cables, and is a natural media on which LO can be delivered to a distant destination stably.

The Ministry of Science and Technology started at 2012 a 973 project, named Microwave Photonics (MWP) Based MMW Packages with Wide Bandwidth and Large Dynamic Range and Their Application (No. 2012CB315600), aiming at solutions of challenges mentioned above. For this purpose, the project set up six tasks focusing on following six aspects, respectively: T1-generation of wide bandwidth MMW based on all optical signal transform in frequency domain; T2-optical phase control mechanism and its application in MMW stable phase transmission over fiber; T3-opto-MMW conversion rules in frequency domain and their applications in dynamic and reconfigurable optical signal processing (OSP) of MMW; T4-ultra-wide optical spectrum based time delay mechanism and its application in MMW true time delay package; T5-components and packages for the opto-MMW signal conversion with dynamic range; and T6-mechanisms and package of MMW low noise and wide tunable optoelectronic oscillator (OEO). Each task is in the charge of a Principal Investigator (PI). Six PIs are Prof. Jungan Miao of Beihang Unviersity, Prof. Yi Dong of Shanghai Jiaotong University, Prof. Xiaoping Zheng of Tsinghua University, Prof. Hanyi Zhang of Tsinghua University, Prof. Song Yu of Beijing University of Post and Telecommunication, Prof. Weiwei Hu of Peking University, respectively. And Prof. Xiaoping Zheng is the chief.

The project has been carried out for four years, and each task almost reaches its intended targets. The next section introduces some achievements of the six tasks.

2 Some achievements

2.1 Linear frequency modulated wave (LFMW) with large time-bandwidth product generated optically

Group of Prof. Xiaoping Zheng successfully generated optically LFMW with 40000 (= 10 μs times 4 GHz). Its basic principle is much different from either what arbitrary waveform generation with short laser pulse (optical frequency comb) or LFMW generation optically with the order of 10 ns in published papers. A novel photonic digital to analog converter (DAC) was proposed [10], based on which the LFMW is obtained. Figure 2 shows one of its waveform in time domain(a), frequency-time line (b), and peak side lobe ratio (PSLR) with Hamming window function (c). Results show less nonlinearity in generated LFMW, which is much better than LFMW generated with electronic DAC. To the best of our knowledge, it is the largest value of time bandwidth product of LFMW generated optically which meets the demands of radars.

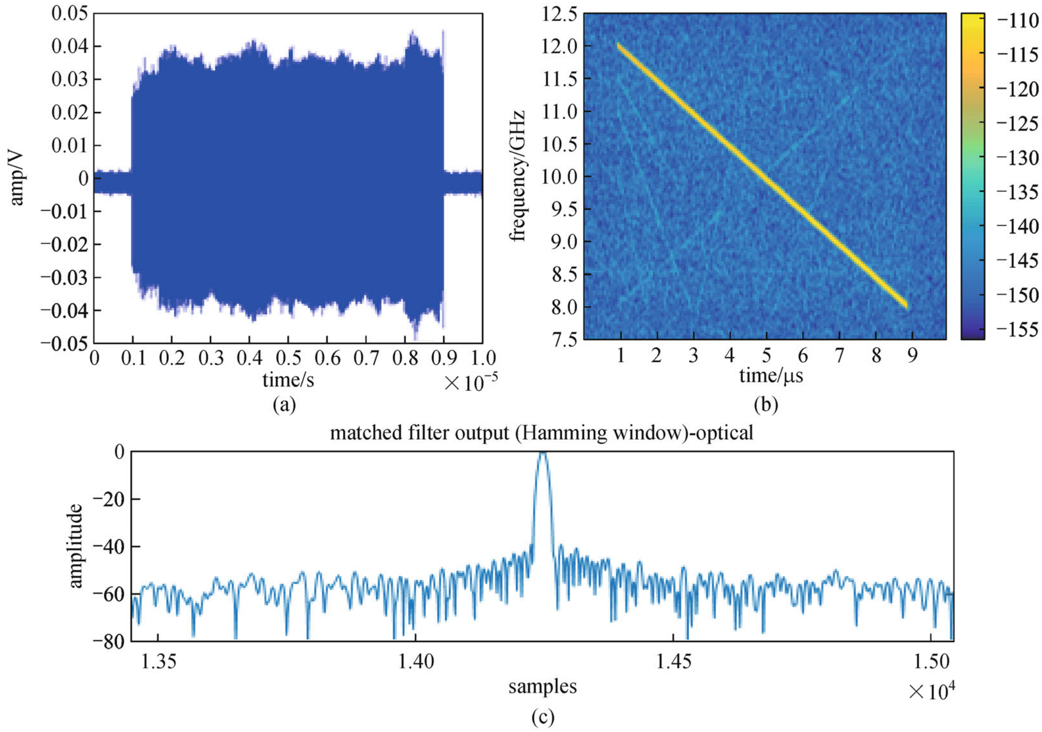


Fig. 2 Linear frequency modulated wave (LFMW) generated optically. (a) its temporal waveform; (b) its time-frequency line; (c) PSLR with Hamming window

2.2 General theory of optical spectrum manipulating for nonlinearity and dispersion compensation for MWP packages and transmission link

Prof. Xiaoping Zheng's Group analyzed the evolution of MMW signals carried optical spectrum through optical components (e.g., Mach-Zehnder modulator (MZM), electro-absorption modulator (EAM), phase modulator (PM), dispersive elements, etc.), obtained the relationship of nonlinear components between electrical domain and optical domain [11], the effect of dispersive elements on optical spectrum [12], and reached the conclusion that by manipulating optical spectrum properly both nonlinearity and dispersion can be compensated for. This Group developed an OSP based on spatial light modulator (SLM) to decrease the effect of nonlinearity on radio over fiber with MZM, EAM and PM, respectively, as shown in Figs. 3(a)–3(c) . Results shows some respective spurious free dynamic range (SFDR) modifying results with MZM and EAM [13,14]. Also by SLM all dispersion of fiber can be eliminated. Figure 4(a) shows an application result to phase noise enhancement in case of LO over fiber to distant antenna [15], it can be seen from the figure that through dispersion compensation, the phase noise of 40 GHz LO with 25 km fiber transmission was modified by 12.6 dB at 10 KHz offset, and Fig. 4(b) shows that signal performance gets better in terms of error vector magnitude (EVM) when dispersion compensation was employed [16].

This Group also managed to use the theory to compensate selectively for 2 order, and 3 order of dispersion, respectively. By compensation for the second dispersion, the true time delay line extends its working frequency bandwidth up to 20 GHz with time delay fluctuation less than 1 ps [17]. And with the help of the third dispersion compensation, MWP filter of finite impulse response (FIR) type realized, for the first time, controllable Q value of MWP when tuning its central frequency [18]. Next, more detailed about MWP filter is introduced.

2.3 Tunable and reconfigurable MWP filter of FIR type

Widely tunable MWP filter with full re-configurability has many applications in many MMW systems. Two difficulties exist in developing such kind of filter: one is how to keep 3-dB bandwidth unchanged when tuning; another is how to realize filter taps with arbitrary complex coefficients which is required for full re-configurability of such type of filter. Prof. Zheng's Group proposed a new concept, named equivalent electrical slicing (EES), replacing optical slicing which is essential conventionally, and pave the way for the solution of two difficulties. The schematic diagram of proposed MWP filter is shown in Fig. 5 [19]. An incoherent broadband optical source (IBOS) together with a Mach-Zender type interferometer with one arm serving as the variable optical carrier time

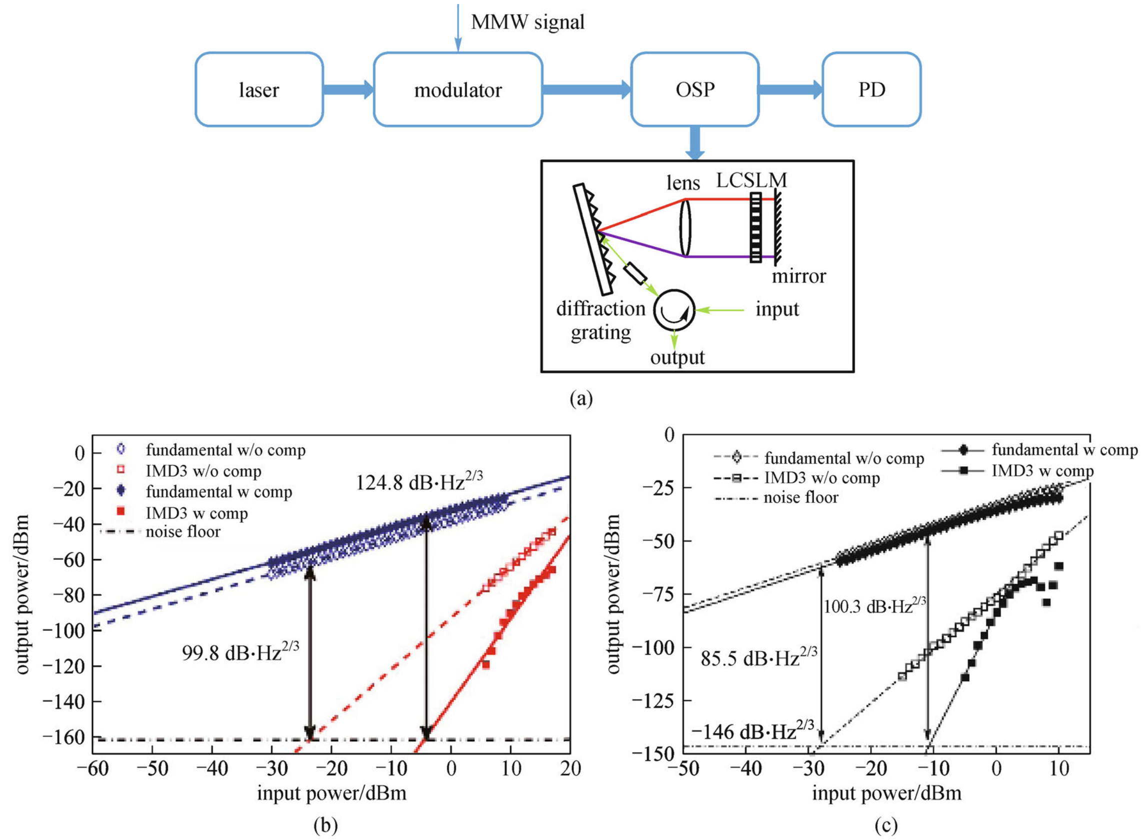


Fig. 3 Nonlinearity compensation based on (a) OSP; compensation results with (b) MZM [13] and (c) EAM [14]. MMW: millimeter wave; OSP: optical signal processing; PD: photodetector; LCSLM: liquid crystal spatial light modulator; IMD3: 3rd order intermodulation distortion

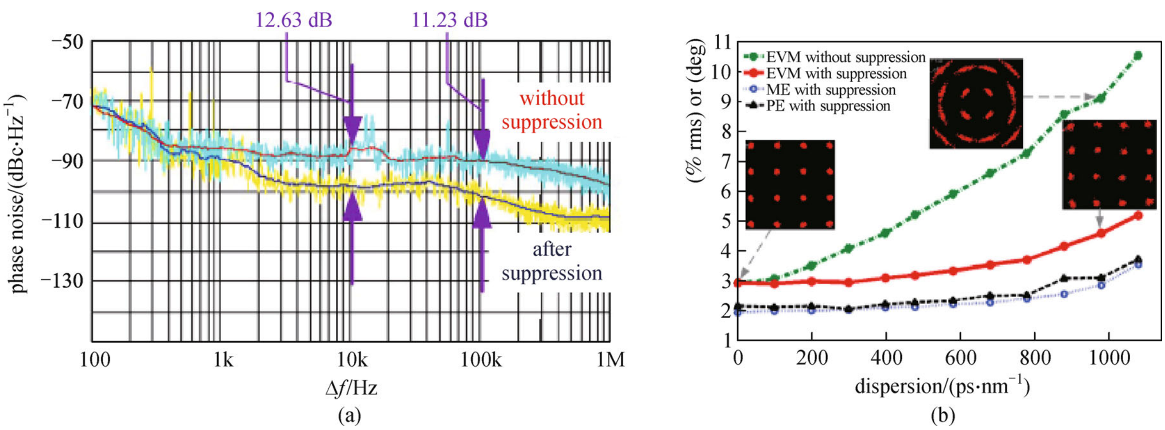


Fig. 4 Local oscillator (LO) over fiber transmission without/with dispersion compensation comparison with regards to (a) LO phase noise with 40 GHz LO frequency and 25 km transmission fiber [15]; (b) EVM, PE, and ME of the 200 Mbps 16 quadrature amplitude modulation (16-QAM) signal with 59 GHz LO frequency and 60 km transmission fiber [15]

(VOCT) constructs a basic structure to realize the EES, and a programmable optical spectrum processor (POSP) is embedded in the VOCT arm, tailoring the optical spectral amplitude and phase to construct with program arbitrary complex taps of the filter. As a result, the arbitrary complex continuous-time impulse responses is obtained, and the proposed MWP filter features frequency responses with arbitrary-shape passband [20]. The filter has a wide tuning range which is only limited by the bandwidth of opto-electrical devices. To guarantee the shape controllable when tuning bandpass center, it is vital to eliminate the third dispersion in the filter [21]. The Group managed to

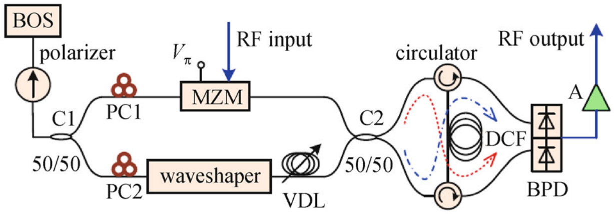


Fig. 5 Experimental setup of the single-bandpass complex-tap microwave photonic filter based on EES [19]. BOS: broadband optical source; C: optical coupler; PC: polarization controller; MZM: Mach-Zehnder modulator; VDL: variable delay line; DCF: dispersion-compensating fiber; BPD: balanced photodetector; A: RF amplifier

selectively compensate for it by POSP with the help of the general theory of optical spectrum manipulating for nonlinearity and dispersion compensation [18]. Figure 6 shows the tenability of the proposed filter. To the best of our knowledge, it is the first time for an IBOS based MWP filter to realize simultaneously single-bandpass, widely tunable, and fully reconfigurable with complex taps [21].

2.4 Tunable optoelectronic oscillator (OEO) with low phase noise

OEO acts as LO in MWP-based MMW systems, tunability and low phase noise are its two basic performances. Conventional OEO uses fiber to form long cavity depressing phase noise, electrical filter to tune output MMW frequency. Because the OEO tuning range depends on that of electrical filter, it is hard to increase this value. The Group from Prof. Zhangyuan Cheng replace electrical filter with MWP filter, extending theoretically the tuning range to THz. This Group developed two kinds of MWP filters for tunable OEO: one is PM-based filter, another an-Stokes stimulated Brillouin scattering (SBS) based OEO [22,23]. Figures 7(a) and 7(b) shows their schematic diagrams, respectively. And they both feature phase noise as low as −120 dBc/Hz at 10 KHz offset. In bid to decrease phase noise further, this Group optimized performances of optical components in the OEO, and managed to depress the phase noise down to around −150 dBc/Hz at 10 KHz offset at 10 GHz.

2.5 LO transmission over fiber with high stability

The Group of Prof. Yi Dong proposed a scheme to compensate for the phase fluctuation along the transmission fiber based on optical frequency adjustment (OFA), as shown in the Fig. 8 [24]. Different from adjusting the time delay induced by noise along the transmission fiber, which is popularly adopted in the released papers, this Group adjusted the optical frequency dynamically such that the phase fluctuation of MMW LO along the transmission fiber can also be compensated for. Experiment results showed that the scheme has many advantages, such as larger compensation range in terms of phase error, wider compensation bandwidth, and strong ability to counter environmental noise, e.g. vibration, temperature change, etc.. The phase error detect with high accuracy is the key technology in order to realize effective OFA. This Group proposed a DHPT method, that is, dual-heterodyne phase error transfer in short, to transfer the phase fluctuation

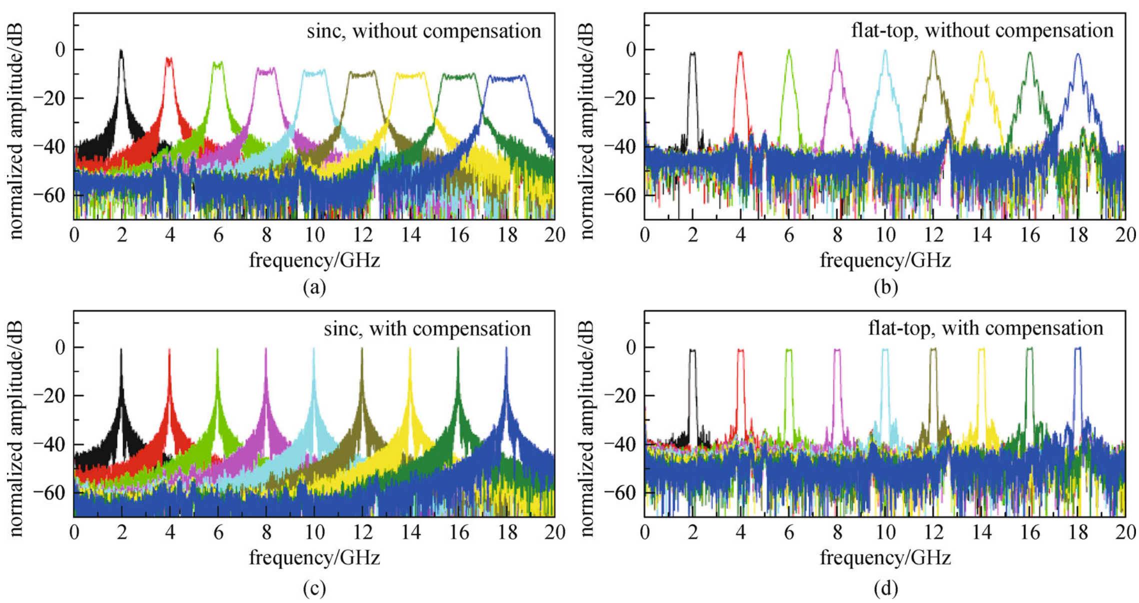
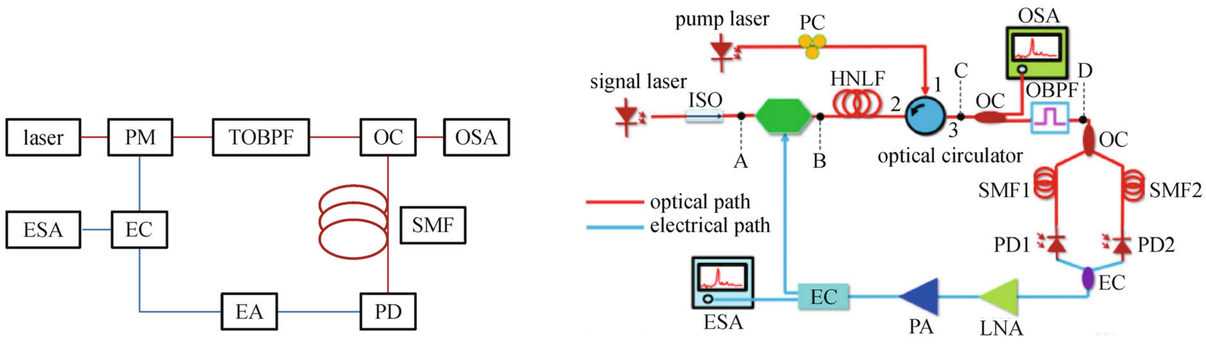


Fig. 6 Tunable RF transfer function with or without TOD compensation when the passband is sinc-shape or flat-top [21]



(a) (b)

Fig. 7 Tunable OEOs by using (a) PM-based filter [22]; (b) an-Stokes SBS [23]. PM: phase modulator; SBS: stimulated Brillouin scattering; TOBPF: tunable optical bandpass filter; OC: optical coupler; OSA: optical spectrum analyzer; SMF: single-mode fiber; PD: photodetector; EA: electricalamplifier; EC: electrical coupler; LNA: low noise amplifier; PA: power amplifier; ESA: electrical spectrum analyzer

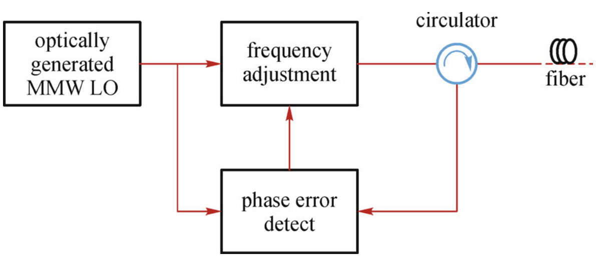


Fig. 8 Schematic diagram of LO stable transmission over fiber

along the transmission fiber identically to a 40 MHz intermediate frequency such that obtained accurate phase error, and then employed a phase locked loop in which OFA was embedded to cancel it [25]. Experiment results showed that the root mean square (RMS) phase jitter in the frequency ranging from 0.01 Hz to1 MHz is less than 0.06 rad up to 400 GHz, and under the same conditions time jitter (RMS) is less than 76 fs at 50 GHz and 22 fs at 400 GHz.

2.6 Down-conversion with gain increase and noise decrease

The Group of Prof. Song Yu proposed an optical carrier reusing based down conversion, as shown in Fig. 9 [26]. Its main elements include two narrowband fiber Bragg gratings (FBGs), and a PM between them. The FBGs transmit sidebands of optical carrier (OC) and reflect OC into the PM so that the OC is kept in the PM to be modulated circularly and does not goes into the photodetector (PD). By such structure, OC is utilized efficiently, optical power for down conversion can be effectively increased, and the down conversion lose can be greatly decreased. Controlled by phase matching in the PM, the

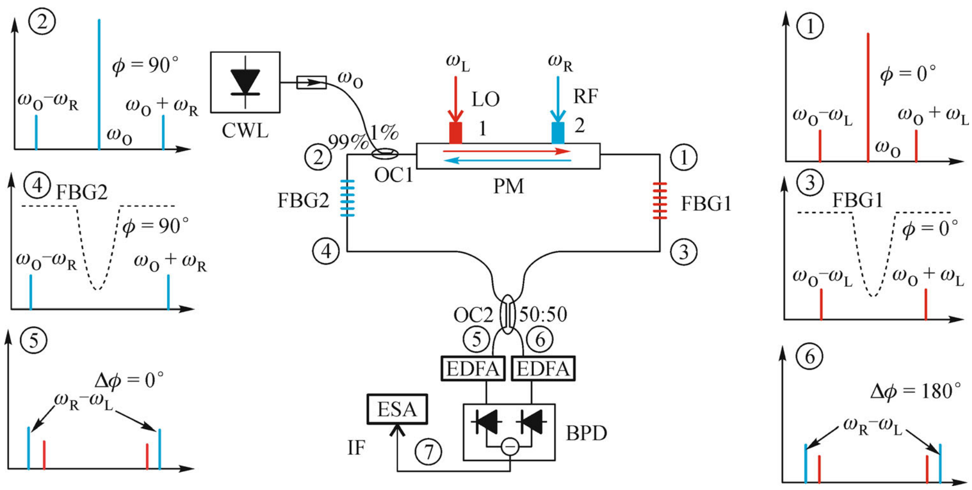


Fig. 9 Diagram of the down-conversion system presented here [25]. ESA, electronic spectrum analyzer. ϕ is the phase of light wave. $\Delta\phi$ is the phase difference of sidebands between LO and RF frequency. Black dotted lines represent the transmitted spectrum of FBGs

forward and reverse OCs are modulated by different frequency signals, respectively. And finally, a balanced PD is employed to improve the gain and reduce the intensity noise further. Experiment results show that 29 dB gain improvement can be obtained compared with the traditional dual-series intensity modulators, and its noise floor is lowered by 12 dB [26].

3 Summary

Through researches for 4 years, the team group of the project have achieved a series of achievements in MWP packages. Some main performance indexes of these packages have reached the demands of MMW system. And some packages have been applied in radars and wireless communication systems, and are not introduced in the paper due to the limitation of the paper length. Currently, a prototype of transceiver (TRX) of W band with IB of 10 GHz based on proposed MWP packages is under construct and test, it is believed that with developed MWP packages, the TRX will have a dynamic range of more than 120 $dB \cdot Hz^{2/3}$.

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