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Shifeng Liu
Dan Zhu
Shilong Pan

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Shifeng Liu,[a,b] Dan Zhu,[a,b,*] and Shilong Pan[a,b,*]
[a]Nanjing University of Aeronautics and Astronautics, Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, College of Electronic and Information Engineering, No. 29 Yudao Street, Nanjing 210016, China
[b]State Key Laboratory of Millimeter Waves, Nanjing 210096, China

Abstract. A wideband signal upconversion and phase shifting scheme based on a frequency tunable optoelectronic oscillator (OEO) are proposed and demonstrated. The OEO performs simultaneously tunable high-quality local oscillator (LO) signal generation, wideband frequency upconversion, and phase shifting within the whole 2π range. With the generated LO tuning from 9.549 to 11.655 GHz, wideband square signals are successfully upconverted to the X band. The phase of the upconverted signal is tuned from 0 to 360 deg. The phase noise of the oscillation signal is about -104 dBc/Hz at 10 kHz offset with or without the injected baseband signal.
 [DOI: 10.1117/1.OE.53.3.036101]

Keywords: upconversion; optoelectronic oscillator; phase shift; polarization modulation; frequency tunable.

Paper 131796 received Nov. 27, 2013; revised manuscript received Jan. 23, 2014; accepted for publication Feb. 6, 2014; published online Mar. 6, 2014.

1 Introduction

Photonic-assisted beamforming for phased array antennas has been widely studied due to the wide operational bandwidth, low weight, small volume, capability of antenna remoting, and immunity to electromagnetic interference brought by the photonic technologies.[1–4] Wideband frequency upconversion[5–8] and phase shifting[9–13] are two of the key functions in the optical beamforming systems. Conventionally, frequency upconversion is realized by electrically mixing an electrical local oscillator (LO) with an intermediate-frequency signal or a baseband signal. The key problems associated with this method are the limited operational bandwidth due to the electronic bottleneck and the poor quality of the high frequency electrical LO.[14,15] Optoelectronic oscillator (OEO), which is an optoelectronic feedback loop consisting of an electro-optic modulator (EOM), an optical fiber delay line, a photodetector (PD), an electrical amplifier, and an electrical bandpass filter (EBPF), has been considered as a high-quality LO due to its ability to generate a low phase noise microwave or millimeter-wave signal in both electrical and optical domains.[16–18] If a lightwave with a baseband signal is injected to the OEO, frequency upconversion can also be implemented because the generated LO would mix with the baseband signal at the EOM of the OEO.[5–8] The key limitation is that the phase shifting function cannot be easily realized especially when the upconverted signal occupies a wide bandwidth. Recently, a frequency and phase tunable OEO based on a polarization modulator (PolM) and a phase-shifted fiber Bragg grating (PS-FBG) were reported.[13] A single-sideband (SSB) polarization-modulated signal is generated by the use of the PolM together with the PS-FBG to maintain the oscillation of the OEO in the loop, and to introduce a phase shift to the oscillation signal at the output branch with the help of a tunable polarizer. The frequency tunability is achieved by tuning the wavelength of the optical carrier. However, the scheme is sensitive to the wavelength drift of the laser diode (LD), and the notch of the PS-FBG has a bandwidth of only 12 MHz, so the system could not be used for wideband signal upconversion and phase shifting. For practical phased array antennas, the phase shift must be performed to wideband signals.

In this paper, wideband signal upconversion and phase shifting based on a frequency-tunable polarization-modulated OEO are proposed and demonstrated. The OEO simultaneously produces tunable high-quality LO signals, implements wideband signal upconversion, and realizes phase shift of the wideband upconverted signals. The phase noise of the oscillation signal keeps almost the same with or without the injected baseband signal.

2 Principle

The schematic diagram of the wideband signal upconversion and phase shifting scheme based on a frequency tunable OEO is shown in Fig. 1. A lightwave from an LD is modulated by a baseband signal to be upconverted at a Mach–Zehnder modulator (MZM) via a polarization controller (PC, PC1). The baseband signal is generated by a pulse pattern generator (PPG). The modulated optical signal is sent to a PolM with its polarization state aligned to have an angle of 45 deg to one principal axis of the PolM via a second PC (PC2). A 10%:90% optical coupler is connected to the PolM to split the polarization-modulated signal into two branches. The 90% branch is used to form the feedback loop for the OEO, which consists of the PolM, two polarization beam splitters (PBSs), three PCs, a PD, a low noise amplifier (LNA), and a tunable EBPF. PC3 is adjusted to let the output signal of PBS1 to be a linearly intensity modulated signal.[18] Then, a polarization multiplexed dual-loop is followed to increase the side mode suppression of the OEO.[19] PD1 is used to perform the optical to electrical

*Address all correspondence to: Dan Zhu, E-mail: danzhu@nuaa.edu.cn; Shilong Pan, E-mail: pans@ieee.org

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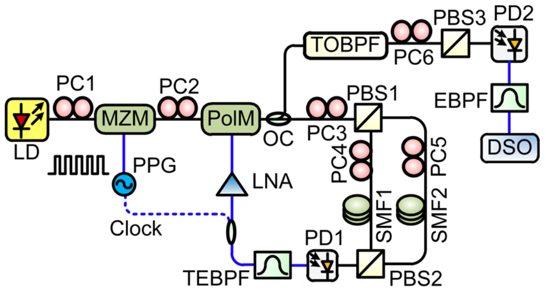

Fig. 1 Experimental setup. LD, laser diode; PC, polarization controller; MZM, Mach–Zehnder modulator; PPG, pulse pattern generator; PolM, polarization modulator; OC, optical coupler; PBS, polarization beam splitter; PD, photodetector; SMF, single mode fiber; LNA, low noise amplifier; TEBPF, tunable electrical bandpass filter; TOBPF, tunable optical bandpass filter; EBPF, electrical bandpass filter; and DSO, digital sampling oscilloscope.

conversion. The obtained electrical signal is filtered by the yttrium-iron-gamet (YIG) tunable EBPF, amplified by the LNA, and then fed back to the RF port of the PolM to form the oscillation. The oscillation frequency is mainly determined by the center frequency of the EBPF which can be tuned by its driven current. As a result, frequency tuning of the OEO can be realized. Due to the high-Q EBPF in the OEO loop, the injected baseband signal almost has no influence on the quality of the oscillation signal.

In the output branch, an upconverted signal will be generated because of the optoelectronic mixing in the PolM. A tunable optical bandpass filter (TOBPF) is followed to convert the double-sideband polarization-modulated signal into an SSB polarization-modulated signal. A PC (PC6) and a PBS (PBS3) are connected to the TOBPF. As described in Ref. 12, the phase of the upconverted wideband signal can be tuned within 2π range while the amplitude keeps unchanged by changing the polarization direction of the SSB signals via PC6. The optical signal is then converted to an electrical signal at a PD (PD2). An EBPF is inserted to select the upconverted signal. Compared with Ref. 13, the upconversion can be realized with a wideband signal, and the phase shift can also be obtained for the wideband upconverted signal, which is highly desirable in the phased array antenna systems.

3 Experimental Results and Discussion

An experiment based on the setup shown in Fig. 1 is carried out. The parameters of the key devices used in this experiment are as follows. The laser source is an LD (Agilent N7714A, Santa Clara) with a stability of 2.5 pm, a wavelength of 1551.496 nm, and an optical power of 15 dBm. The MZM (Fujitsu Optical Component Limited, Kanagawa, Japan, FTM7938EZ-A) has a 3-dB bandwidth of 40 GHz. The baseband signal to be upconverted is generated by a PPG (Anritsu MP1763, Kanagawa, Japan). The PolM (Versawave Technologies, Burnaby BC, Canada) has a bandwidth of 40 GHz and a half-wave voltage of 3.5 V. PD1 has a bandwidth of 50 GHz and a responsivity of 0.65 A/W. The tunable EBPF (TEBPF) is a tunable YIG EBPF with a 3-dB bandwidth of 25 MHz and a frequency tuning range from 8 to 12 GHz. The gain of the LNA is about 40 dB. An electrical spectrum analyzer (ESA, Agilent E4447A, Santa Clara, 3 Hz to 43 GHz) with a phase noise measurement module is used to measure the electrical spectra and an optical spectrum

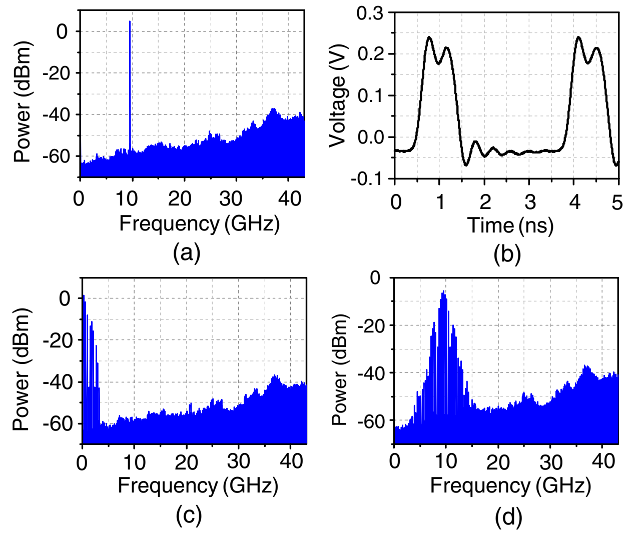

Fig. 2 (a) The electrical spectrum of the optoelectronic oscillator (OEO) signal at 9.549 GHz; the (b) waveform and (c) electrical spectrum of the baseband signal; and (d) the electrical spectrum of the upconverted signal.

analyzer (Yokogawa AQ6370C, Tokyo, Japan) with a resolution of 0.02 nm is employed to monitor the optical spectra. The EBPF used to select the upconverted signal has a working bandwidth of 4 to 15 GHz. In addition, a 40-GHz digital sampling oscilloscope (Agilent 86100A, Santa Clara) is used to observe the waveforms.

Figure 2(a) shows the electrical spectrum of the OEO signal at 9.549 GHz, which is achieved by setting the driven current of the YIG EBPF to be 0.556 A. The 9.549-GHz signal is introduced as the external clock of the PPG. By setting a pattern of "0000 1111 1111 0000 0000 0000 0000 0000," a square waveform as shown in Fig. 2(b) is generated, filtered by a 2.63-GHz low-pass filter and applied to the MZM. The square waveform has a period of 3.35 ns corresponding to a repetition rate of 298.5 MHz. Figure 2(c) shows the electrical spectrum of the baseband signal and Fig. 2(d) shows that of the upconverted signal. As can be seen, the baseband signal is successfully upconverted to 9.549 GHz.

Due to the high-Q EBPF involved in the OEO loop, the baseband signal will be effectively eliminated, thus the injected baseband signal should have almost no influence on the phase noise performance of the oscillation signal.[6,8] To verify this, the influence of the applied baseband signal to the quality of the OEO signal is investigated. Figure 3 shows the SSB phase noise spectra of the 9.549-GHz

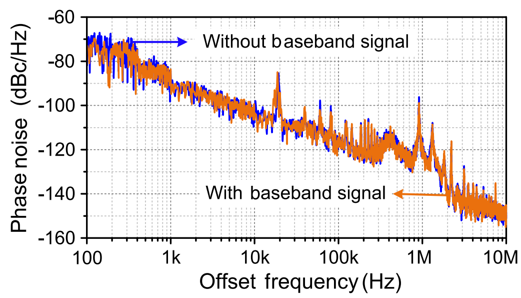

Fig. 3 Single-sideband phase noise spectra of the oscillation signal in the OEO loop with and without the baseband signal applied to the MZM.

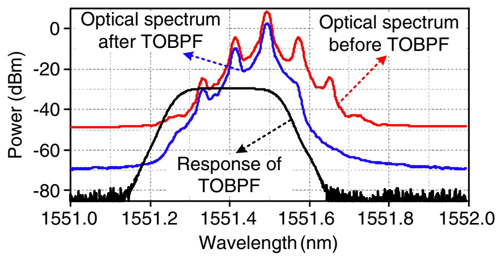

Fig. 4 Optical spectra of the signals before and after the TOBPF and the transmission response of the TOBPF.

oscillation signal in the OEO loop with and without the baseband signal applied to the MZM. The two curves are superimposed, which demonstrate that the injected baseband signal has almost no influence on the phase noise performance of the oscillation signal. For both situations, the phase noise is about -104 dBc/Hz at10 kHz offset.

Figure 4 shows the transmission response of the TOBPF and the optical spectra of the optical upconverted signal before and after the TOBPF. As can be seen, the right sidebands are effectively removed, so the SSB polarization modulation is successfully realized. By tuning PC6 to change the polarization direction of the SSB polarization-modulated signal, the phase of the upconverted wideband signal can be tuned within 2π range while the amplitude keeps unchanged.

The phase shift of the upconverted wideband signal is also tuned by simply adjusting PC6. With the initial waveform (blue curve) of the upconverted signal shown in Fig. 5(a), Figs. 5(b)–5(e) show the measured and calculated waveforms of the upconverted signals with the phase shifts of 90, 180, 270, and 360 deg. As can be seen, the two kinds of curves are superimposed in all cases. Thus, the phase of the upconverted wideband signal is successfully tuned with a full-2π range.

The tunability of the OEO is realized by adjusting the driven current of the YIG BPF.[18] By tuning the driven current to 0.682 A, the oscillation frequency is tuned to be 11.655 GHz. Figure 6 shows the measured and calculated

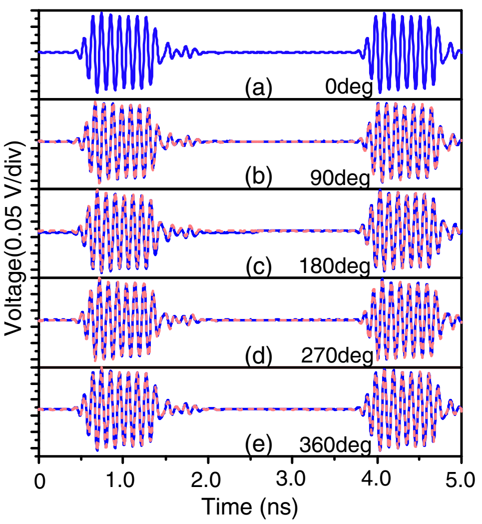

Fig. 5 Measured (blue solid curves) and calculated (red dashed curves) waveforms of the upconverted signals with phase shifts of (a) 0 deg, (b) 90 deg, (c) 180 deg, (d) 270 deg, and (e) 360 deg when the OEO at 9.549 GHz.

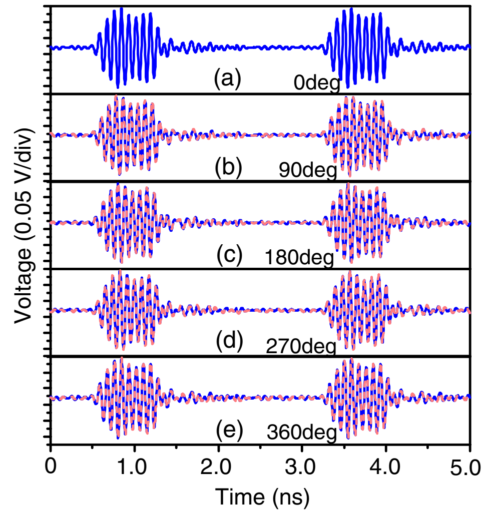

Fig. 6 Measured (blue solid curves) and calculated (red dashed curves) waveforms of the upconverted signals with phase shifts of (a) 0 deg, (b) 90 deg, (c) 180 deg, (d) 270 deg, and (e) 360 deg when the OEO at 11.655 GHz.

waveforms of the upconverted signals with the phase shifts varied in the range of [0 deg, 360 deg]. Again, the measured waveforms match well with the calculated curves.

4 Conclusion

We proposed and demonstrated a wideband signal upconversion and phase shifting scheme based on a frequency tunable OEO. Wideband signals are successfully upconverted to the center frequencies tuning from 9.549 to 11.655 GHz and a tunable phase of the wideband upconverted signals from 0 to 360 deg is realized. Due to the high-Q EBPF incorporated in the OEO loop, the phase noise performance keeps almost the same with or without the injected baseband signal. The phase tunability within the whole 2π range is realized by simply tuning the polarization direction of the polarizer. The proposed scheme combines the functions of tunable low phase noise microwave signal generation, wideband baseband signal upconversion, and phase shifting of the wideband upconverted signal, which may find applications in optical beamforming systems for intelligent wireless communications and radars.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China (61201048, 61107063), the National Basic Research Program of China (2012CB31575), the Natural Science Foundation of Jiangsu Province (BK2012381, BK2012031), the Aviation Science Foundation of China (2013ZC52040, 2012ZD52052), the Postdoctoral Science Foundation of China (2013T60533, 2012M521078), the Jiangsu Planned Projects for Postdoctoral Research Funds (1102054C), and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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Biographies of the authors are not available.