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Generation of an orthogonally polarized dual-wavelength optical signal with large wavelength-spacing tunability by using an integrated modulator and a Sagnac loop

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Abstract A tunable orthogonally polarized dual-wavelength optical signal generator is proposed based on an integrated dual-polarization quadrature phase shift keying modulator, a polarizer and a Sagnac loop. By driving the integrated modulator with an RF signal, an optical signal with two orthogonal polarization states is generated. Leading the polarization multiplexing optical signal to a polarizer with a specific principal axis, the low-order optical components of the signal are cancelled each other, while two high-order sidebands with a wavelength spacing of eight, twelve or sixteen times the frequency of the RF signal reserved. After that, a Sagnac loop is used to make the two sidebands separated and combined with orthogonal polarization states. The proposed approach features large wavelength spacing and good tunability for the generated optical signal. An experiment is performed. The generation of an orthogonally polarized dual-wavelength optical signal with wavelength spacing at 32, 80 and 91.2 GHz is verified by using an RF signal with frequency at 4, 10 and 11.4 GHz.

Keywords Orthogonal polarization · Dual-wavelength signal · Microwave photonics

1 Introduction

The orthogonally polarized dual-wavelength optical signal consists of two phase-correlated wavelengths with orthogonal polarization states. It can offer the promise of parallel signal processing and compact integration, improve the spectral efficiency and reduce the intermodulation. These advantages make the orthogonally polarized dual-wavelength

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signal has extensive applications in microwave photonics filtering, antenna beamforming, waveform shaping, and nondestructive imaging (Wang et al. 2013; Xing et al. 2015).

An orthogonally polarized dual-wavelength optical signal can be directly generated by modulating an RF signal with an optical carrier through an acousto-optic modulator (Dolfi et al. 1996), a polarization modulator (PolM) followed by an optical filter (OF) (Wang et al. 2013; Pan and Zhang 2012; Zhang and Pan 2013), or a specially designed single sideband modulator which consists of two parallel PolMs (Campillo 2007). The main drawback of these schemes is that the wavelength spacing of the generated optical signal is small and the tunability is also limited due to the bandwidth of the modulator or the OF. An orthogonally polarized dual-wavelength signal can also be generated by sending two phase-correlated optical wavelengths to a frequency and polarization-dependent component (Li et al. 2010; Zheng et al. 2014; Sagues and Loayssa 2010; Li et al. 2012). In this method, two optical sidebands with identical polarization state are first generated by modulating an RF signal with an optical carrier. After that, the sidebands are made orthogonally polarized by using a differential group delay (DGD) element (Li et al. 2010), a polarization maintaining fiber Bragg grating (PM-FBG) (Zheng et al. 2014), or a simulated Brillouin scattering (SBS) structure (Sagues and Loayssa 2010; Li et al. 2012). However, the DGD and the PM-FBG based schemes have a very limited wavelength spacing tuning range because of the frequency-dependent response of the devices, while for the SBS-based scheme, the precise orthogonality between the two optical sidebands is difficult to realize and the system is complicated. On the other hand, to overcome the restriction of the wavelength spacing caused by the bandwidth of the modulator and electrical devices, frequency multiplication is highly desired when performing the generation of an orthogonally polarized dual-wavelength signal. Previously, orthogonally polarized dual-wavelength optical signal with a wavelength-spacing of two or four times the input RF frequency has been generated (Chi and Yao 2008; Liu et al. 2014; Li et al. 2011, 2016), but the frequency multiplication factor is small, makes it can hardly support the applications when a wavelength spacing larger than 100 GHz is needed.

In this paper, we propose an approach to generate an orthogonally polarized dual-wavelength signal with large wavelength spacing and good tunability. One key point of the scheme is that the wavelength-spacing of the generated optical signal has high frequency multiplication factor. By using an integrated dual polarization quadrature phase shift keying modulator (DP-QPSK), a polarization multiplexing optical signal is generated. Then, the optical signal is put into a polarizer (Pol). By adjusting the principal axis of the Pol, the low-order optical components can be suppressed and only the two high-order sidebands reserved. Another point of the scheme is the processing of the polarization state of the dual-wavelength signal. By using an FBG-incorporated Sagnac loop, which we previously demonstrated in Li et al. (2016), the two sidebands of the dual-wavelength optical signal can be orthogonally polarized. The key advantage of this approach is the large wavelength spacing and good tunability of the generated optical signal. Note that the frequency multiplication factor of the wavelength-spacing for the generated orthogonally polarized signal has potential capability to be sixteen (Li et al. 2015), the wavelength spacing can be possibly tuned from several MHz to THz. In addition, the frequency-multiplied operation of the wavelength-spacing is achieved through a single modulator and filter-free, thus the system is simple and compact.

2 Principle

Figure 1a shows the schematic diagram of the proposed orthogonally polarized dual-wavelength optical signal generator. A linearly polarized light wave from a tunable laser source (TLS) is sent to an integrated DP-QPSK modulator. The modulator comprises a 3-dB optical coupler, two parallel placed QPSK modulators and a polarization beam combiner (PBC), as shown in Fig. 1b. The two QPSK modulators have identical parameters and each of them consists of two identical sub-MZMs placed in a main MZM. An RF signal from a microwave signal generator (MSG) is first divided into two paths, and then each of the paths further divided into two parts through an electrical 90 degree hybrid and applied to the two RF ports of the upper and bottom QPSK modulators, respectively. In one path, an electrical power amplifier (PA) is inserted, as shown in the figure, to generate two different modulation indices for the two QPSK modulators, i.e. a large value for the upper modulator and a relatively small value for the bottom modulator. When the two QPSK modulators have identical DC bias points, two optical signals with the same order sidebands but different powers will be generated. The output optical signal at the upper QPSK modulator can be expressed by the Jacobi–Anger expansion as

$$\begin{aligned} E_{up}(t) &= \frac{\sqrt{2}}{8} E_{in} \exp(j\omega_c t) \left\{ \begin{array}{l} \{\exp[jm\sin(\omega t)] + \exp[-jm\sin(\omega t)]\exp(j\theta_1)\}\exp(j\theta_3) \\ + \exp[jm\cos(\omega t)] + \exp[-jm\cos(\omega t)]\exp(j\theta_2) \end{array} \right\} \\ &= \frac{\sqrt{2}}{8} E_{in} \exp(j\omega_c t) \sum_{n=-\infty}^{\infty} \left\{ \begin{array}{l} [1 + (-1)^n \exp(j\theta_1)]\exp(j\theta_3) \\ + [1 + (-1)^n \exp(j\theta_2)]\exp\left(j\frac{n\pi}{2}\right) \end{array} \right\} J_n(m)\exp(jn\omega t) \end{aligned} \tag{1}$$

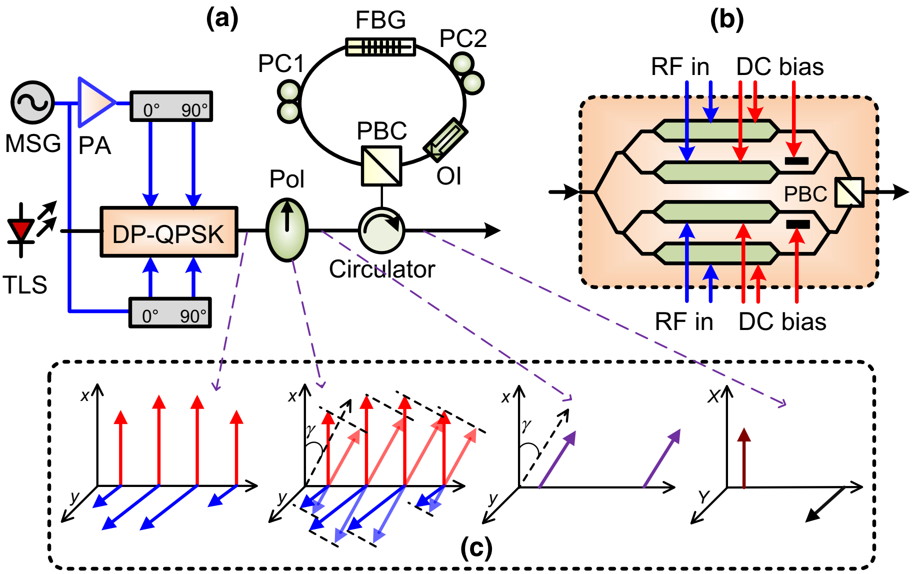

Fig. 1 **a** Schematic diagram of the proposed orthogonally polarized dual-wavelength signal generator. **b** Illustration of the DP-QPSK modulator. **c** Polarization states of the optical signals

where the insertion loss of the modulator is neglected, E_{in} and ω_c are the amplitude and angular frequency of the input light, ω is the angular frequency of the RF signal, m is the modulation index, θ_1, θ_2 and θ_3 are the DC bias phases of the two sub-MZMs and the main MZM, respectively, J_n is the nth-order Bessel function of the first kind.

The following two conditions are considered to generate two high-order sidebands with low-order components.

$$E_{up}(t) = \frac{\sqrt{2}}{2} E_{in} \exp(j\omega_c t) \sum_{n=-\infty}^{\infty} \begin{cases} J_{4n}(m) \exp(j4n\omega t) & \theta_1 = \theta_2 = \theta_3 = 0 \\ -J_{4n+2}(m) \exp[j(4n+2)\omega t] & \theta_1 = \theta_2 = 0, \theta_3 = \pi \end{cases} \quad (2)$$

The bottom QPSK modulator has identical DC bias phases as the upper QPSK modulator, but with a different modulation index of β. At the output of the integrated modulator, the optical signals from the two QPSK modulators are combined with orthogonal polarization states through the PBC. Then, the optical signal at the output of the integrated modulator can be expressed as

$$E_{int}(t) = -\frac{1}{2} E_{in} \exp(j\omega_c t) \sum_{n=-\infty}^{\infty} \begin{cases} -[\vec{x}J_{4n}(m) + \vec{y}J_{4n}(\beta)] \exp(j4n\omega t) & \theta_1 = \theta_2 = \theta_3 = 0 \\ [\vec{x}J_{4n+2}(m) + \vec{y}J_{4n+2}(\beta)] \exp[j(4n+2)\omega t] & \theta_1 = \theta_2 = 0, \theta_3 = \pi \end{cases} \quad (3)$$

where x and y represent the principal axes of the PBC.

The output signal from the DP-QPSK modulator is then sent to a Pol. The principal axis of the Pol is aligned at an angle of γ relative to the x direction, as shown in Fig. 1c. The output signal of the Pol is

$$E_{Pol}(t) = -\frac{1}{2} E_{in} \exp(j\omega_c t) \sum_{n=-\infty}^{\infty} \begin{cases} -\begin{bmatrix} J_{4n}(m)\cos\gamma \\ +J_{4n}(\beta)\sin\gamma \end{bmatrix} \exp(j4n\omega t) & \theta_1 = \theta_2 = \theta_3 = 0 \\ \begin{bmatrix} J_{4n+2}(m)\cos\gamma \\ +J_{4n+2}(\beta)\sin\gamma \end{bmatrix} \exp[j(4n+2)\omega t] & \theta_1 = \theta_2 = 0, \theta_3 = \pi \end{cases} \quad (4)$$

By adjusting the modulation indices and the principal axis of the Pol, one of the following conditions can be satisfied

$$\begin{array}{ll} J_0(m)\cos\gamma + J_0(\beta)\sin\gamma = 0 & \theta_1 = \theta_2 = \theta_3 = 0 \\ J_2(m)\cos\gamma + J_2(\beta)\sin\gamma = 0 & \theta_1 = \theta_2 = 0, \theta_3 = \pi \\ J_4(m)\cos\gamma + J_4(\beta)\sin\gamma = 0 & \theta_1 = \theta_2 = \theta_3 = J_0(m) = J_0(\beta) = 0 \end{array} \quad (5)$$

As a result, the low-order components will be suppressed while two high-order sidebands with identical polarization state are obtained. As we previously analyzed in Gao et al. (2015), two reserved sidebands have a wavelength spacing of eight, twelve or sixteen times the frequency of the RF signal.

After that, the two optical sidebands are sent to an optical circulator and a Sagnac loop, which we have previously demonstrated in Li et al. (2016).The loop consists of a PBC, an optical isolator (OI), a FBG and two PCs. In the loop, the two optical sidebands are separated by the FBG and combined again with orthogonal polarization states through the PBC. The output signal of the loop is given by

$$E_{out}(t) \propto [J_4(m)\cos\gamma + J_4(\beta)\sin\gamma]\left[\vec{X}\exp[j(\omega_c - 4\omega)t] + \vec{Y}\exp[j(\omega_c + 4\omega)t]\right]\theta_1 = \theta_2 = \theta_3 = 0 \quad (6)$$

$$E_{out}(t) \propto [J_6(m)\cos\gamma + J_6(\beta)\sin\gamma]\left[\vec{X}\exp[j(\omega_c - 6\omega)t] + \vec{Y}\exp[j(\omega_c + 6\omega)t]\right]\ \theta_1 = \theta_2 = \theta_3 = \pi \quad (7)$$

$$E_{out}(t) \propto [J_8(m)\cos\gamma + J_8(\beta)\sin\gamma]\left[\vec{X}\exp[j(\omega_c - 8\omega)t] + \vec{Y}\exp[j(\omega_c + 8\omega)t]\right]\ \theta_1 = \theta_2 = \theta_3 = J_0(m) = J_0(\beta) = 0 \quad (8)$$

where X and Y represent the principal axes of the PBC in the loop. As can be seen, an orthogonally polarized dual-wavelength optical signal with a wavelength spacing of eight, twelve or sixteen times the input RF frequency is generated at the output of the Sagnac loop.

Figure 1c shows the polarization states of the optical signals in the scheme, as shown in the figure, a polarization multiplexing optical signal is first generated through the DP-QPSK modulator, then a single polarization state dual-wavelength optical signal is obtained after the Pol, finally, an orthogonally polarized dual-wavelength signal is generated through the Sagnac loop. The proposed scheme exhibits good frequency tunability, as described in Li et al. (2016). The minimum wavelength spacing is restricted to half of the notch bandwidth of the FBG while the maximum tunable range is eight, twelve or sixteen times the bandwidth of the microwave devices and the modulator. As a result, the wavelength spacing and its tuning range can be as large as hundreds of GHz.

3 Experiment results and discussions

An experiment based on the setup shown in Fig. 1a is performed. Due to the restriction of the modulation index of the modulator, only the frequency-octupled is demonstrated. On the other hand, to simplify the scheme, in the experiment, the upper QPSK modulator is driven by the RF signal while the bottom modulator is only DC biased, as demonstrated in Gao et al. (2015).

First, the transmission and reflection spectra of the FBG are measured. It can be observed in Fig. 2 that the central wavelength of the FBG is 1551.072 nm, the notch of the

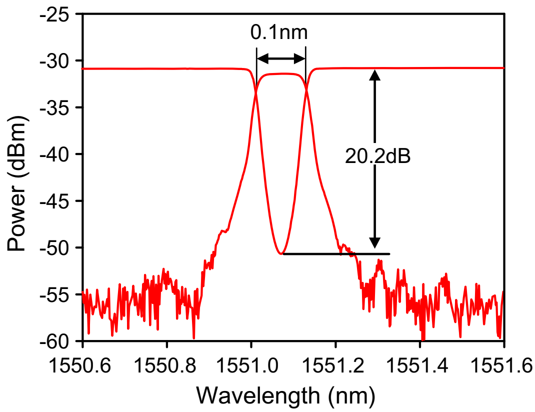

Fig. 2 Transmission and reflection spectra of the FBG

FBG is about 20.2 dB and the 3-dB bandwidth is about 0.1 nm. The FBG can be used to efficiently separate two wavelengths spacing more than 6 GHz.

Then, a light wave from a TLS (Agilent N7714A) with a power of 13 dBm is wavelength tuned to 1551.395 nm. The DP-QPSK modulator is a commercial available device (Fujitsu FTM7977HQA) which has a 3-dB bandwidth of $\sim$ 23 GHz. An RF signal at 10 GHz is generated by a MSG (Agilent E8257D) and amplified more than 30 dBm through a PA (Agilent 83020A). A tunable attenuator is placed after the PA to adjust the modulation index of the modulator. Figure 3 shows the optical spectrum at the output of the Pol. As can be seen, the two forth-order sidebands are generated with the optical carrier suppressed. Several undesired sidebands are also generated due to the finite extinction ratio of the modulator (20 dB for the sub-MZMs and 22 dB for the main-MZMs). The optical spurious ratio (OSR) of the generated dual-wavelength signal is 22.1 dB, and the wavelength spacing of the generated two sidebands is 80 GHz, which is eight times the input RF signal frequency.

The two forth-order sidebands are then amplified to 16 dBm by an EDFA and sent to a Sagnac loop to make orthogonally polarized. To verify the polarization property of the generated dual-wavelength optical signal, another PC followed by a PBC are temporarily connected to the output of the optical circulator. Figure 4 shows the optical spectra of the optical signals at the two output ports of the PBC. As can be seen, two optical sidebands are well separated in the two orthogonal polarization directions, and each of the optical sidebands is suppressed more than 38.7 dB by the polarization selection, which demonstrates that the two optical sidebands are orthogonally polarized.

To demonstrate the wavelength spacing tunability, the MSG is tuned to 4 GHz while the TLS is tuned to 1551.196 nm. Figure 5 shows the spectrum of the generated optical signal at the output of the Pol. As shown in the figure, the output signal has two forth-order optical sidebands with a wavelength spacing of 32 GHz and an OSR of 14.1 dB. Figure 6 shows the polarization property of the generated orthogonally polarized dual-wavelength signal, each of the optical sidebands is suppressed more than 29.4 dB by the polarization selection. Then, a dual-wavelength optical signal with a wavelength spacing of 91.2 GHz is generated by adjusting the frequency of MSG to 11.4 GHz and the wavelength of the TLS to 1551.400 nm. Figure 7 shows the spectrum of the generated optical signal after the Pol, the OSR of the signal is 17.2 dB. Figure 8 shows the polarization property of the generated orthogonally polarized dual-wavelength signal, each of the optical sidebands is

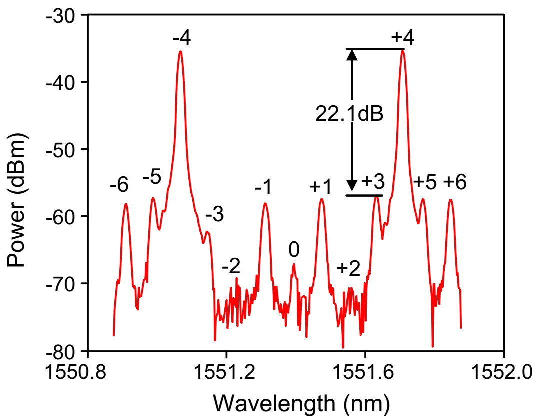

Fig. 3 The output optical spectrum of the Pol with a 10-GHz RF signal

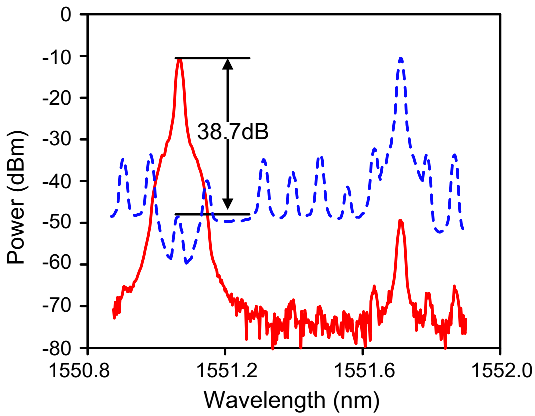

Fig. 4 The optical spectra at the two outputs of the PBC with a 10-GHz RF signal. The real and dashed lines show the two outputs respectively

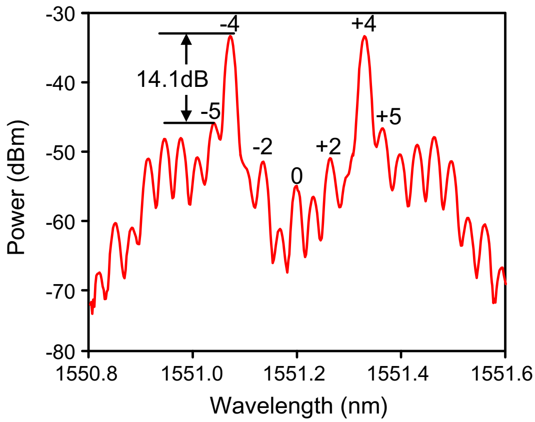

Fig. 5 The output optical spectrum of the Pol with a 4-GHz RF signal

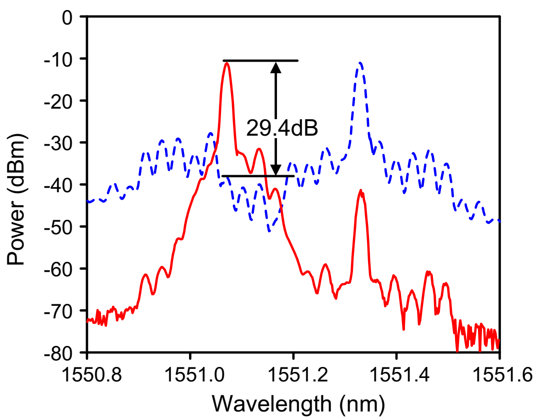

Fig. 6 The optical spectra at the two outputs of the PBC with a 4-GHz RF signal. The real and dashed lines show the two outputs respectively

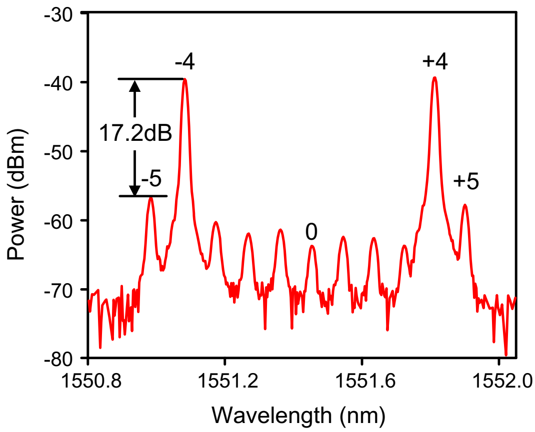

Fig. 7 The output optical spectrum of the Pol with an 11.2-GHz RF signal

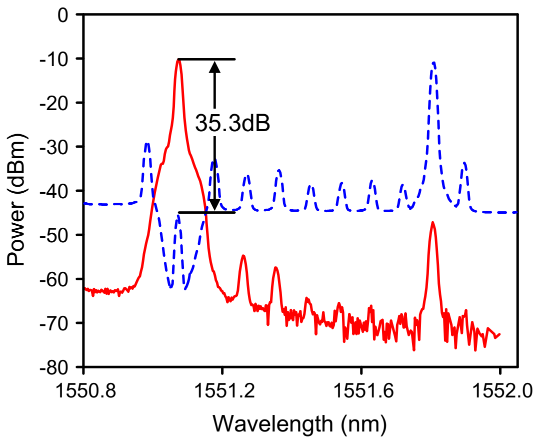

Fig. 8 The optical spectra at the two outputs of the PBC with an 11.2-GHz RF signal. The real and dashed lines show the two outputs respectively

suppressed more than 35.3 dB by the polarization selection. Due to the finite extinction ratio of the modulator, the OSR of the generated signal is limited, but it can be improved by using a modulator with better performance.

Thanks to the frequency-octupled operation, the wavelength spacing of the generated dual-wavelength signal can be as high as 184 GHz theoretically when the bandwidth of the modulator (23 GHz) is considered.

The stability of the system is mainly affected by two problems. One is the drifting of the DC bias points in the modulator, which will induce residual sidebands and deteriorate the OSR of the dual-wavelength signal, but it can be eliminated by employing an automatic bias controller (i.e. YY LABS Inc. Modulator Bias Controller family) in the system. Another is the variation of the FBG and the Sagnac loop, which will deteriorate the orthogonal polarization property and cause phase difference between the two wavelengths, however, this problem can be resolved by packing the FBG and the Sagnac loop.

4 Conclusions

In conclusion, we have proposed a novel approach for the generation of an orthogonally polarized dual-wavelength optical signal based on a DP-QPSK modulator and a Sagnac loop. By adjusting the bias voltages and modulation indices of the modulator, a polarization multiplexing optical signal is generated. By sending the signal to a Pol with a specific principal axis, the low-order optical components are suppressed while two high-order sidebands reserved. Finally, the two optical sidebands are made orthogonally polarized in a FBG-incorporated Sagnac loop. The generated optical signal has a large wavelength spacing, the frequency multiplication factor of the proposed scheme can be as high as eight, twelve or sixteen. Generation of a frequency-octupled orthogonally polarized dual-wavelength signal is experimentally verified. The approach has potential applications in parallel communication systems, radar and electrical-ware systems where high frequency, broad bandwidth and frequency agility are needed.

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