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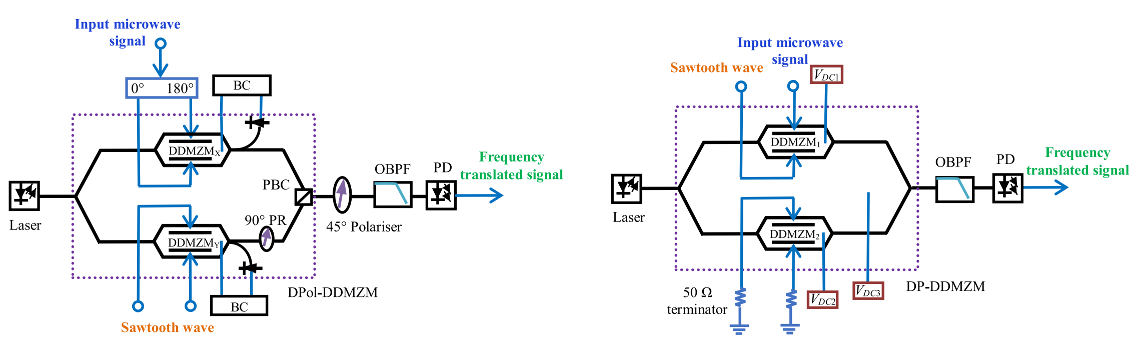

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Microwave Photonic Frequency Translators With Large Spurious Suppression and Wide Bandwidth

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Abstract: Two new photonics-based microwave frequency translators are presented. They are based on Serrodyne modulation to frequency translate an optical carrier, which beats with a microwave signal sideband at a photodetector to generate a frequency translated microwave signal. The proposed frequency translators have a simple structure, a wide bandwidth and a large spurious signal suppression ratio. Experimental results are presented for the novel structures, which demonstrate the realisation of microwave signal frequency translation with $>$38 dB spurious signal suppression over a wide microwave signal frequency range of 2 to 18 GHz and with $>$35 dB spurious signal suppression for a translation rate of 500 Hz to 3 MHz. Frequency translation of an 80 MHz bandwidth frequency modulated continuous wave signal at 5.88 GHz frequency with $>$34 dB spurious signal suppression is also demonstrated.

Index Terms: Optical signal processing, microwave frequency translation, optical modulators, Serrodyne modulation.

1. Introduction

Microwave signal processing involves modification of the amplitude, frequency or phase of a microwave signal. Modifying a microwave signal frequency is usually accomplished by a frequency mixer. Mixers produce an RF/IF signal with a frequency equal to the sum or difference of the input IF/RF signal frequency and the local oscillator (LO) frequency. The frequency difference between the mixer input and output signals can be as large as tens of GHz. Mixers can also be used to generate a microwave signal with a small frequency difference compared to the input signal. This is needed in electronic countermeasures (ECM) systems to generate a false target signal [1] and in high-speed railway mobile communication to compensate for the Doppler effect [2]. However, it is difficult to design a mixer that produces a frequency-translated signal with small adjacent spurious signals. Such requirement is important in ECM systems in order to avoid a radar system knows its signal is being jammed. In addition to electronic warfare and communication, microwave signal frequency translators have applications in reflectometer systems, frequency scanned antennas, frequency comb generators and radar pulse shapers [3], [4].

Another technique for modifying a microwave signal frequency is called Serrodyne frequency translation [5]. This is based on using a sawtooth wave to phase modulate a microwave signal. The frequency of the output microwave signal is either $f_{RF} + f_{saw}$ or $f_{RF} - f_{saw}$ where f_{RF} is the

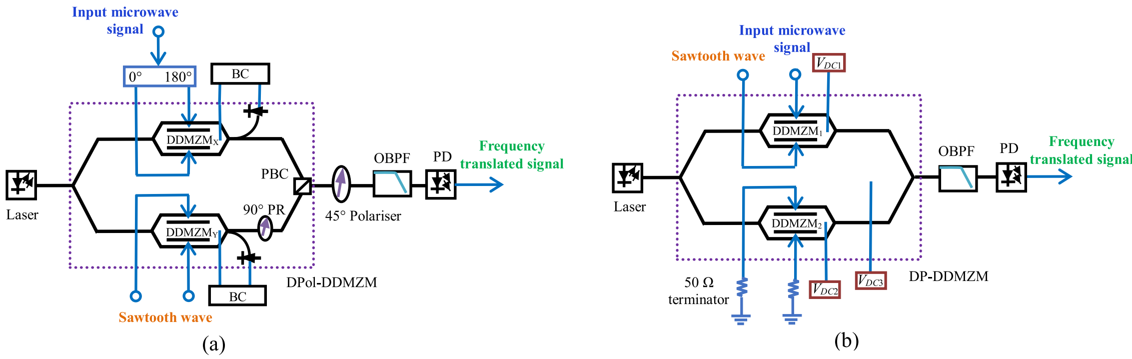


Fig. 1. Structures of the new microwave photonic frequency translator based on (a) a DPol-DDMZM and (b) a DP-DDMZM.

original input microwave signal frequency and f_{saw} is the sawtooth wave frequency. The spurious signals generated by the Serrodyne frequency translation process can be much smaller than that generated by a mixer. For example, typical commercial electronic frequency translators have 25 dB carrier suppression and 20 dB sideband suppression [6]. An electronic frequency translator with greater than 34 dB spurious signal suppression can be made [7]. However, it only covers a 15% bandwidth at the X band. There is no way for electronic frequency translators to simultaneously have a wide bandwidth and large spurious signal suppression. Broadband frequency translators are needed in ECM systems for wideband radars and for a radar system where its signal frequency keeps changing to prevent jamming. Realising microwave signal frequency translation through microwave photonic techniques provide a solution. Microwave photonic signal processing also has the advantage of immunity to electromagnetic interference [8], which is an important requirement in electronic warfare systems. Previous reported microwave photonic Serrodyne frequency translators have a complex structure that involves multiple optical modulators and several electronic components [9], have a limited spurious signal suppression ratio of only 23 dB [10] or have a very small frequency translation rate of less than 100 Hz [11].

Two novel microwave photonic frequency translator structures are presented. They are based on using an optical frequency translation technique to frequency translate an optical carrier. A frequency translated microwave signal is generated when the frequency translated optical carrier beats with a microwave signal sideband at the photodetector. Experimental results are presented, which demonstrate microwave signal frequency translation with large spurious signal suppression over a wide frequency range. Frequency translation of a microwave signal with a band of frequency is also demonstrated.

2. Operation Principle and Analysis

The new microwave photonic frequency translator topologies are shown in Fig. 1. They are both based on a single integrated electro optic modulator, which consists of two dual-drive Mach Zehnder modulators (DDMZMs) connected in parallel, and an optical bandpass filter (OBPF) for removing one microwave signal sideband. In the first topology [Fig. 1(a)], an input microwave signal is split into two via a 180° hybrid coupler before applying to a DDMZM (DDMZM$_\mathrm{X}$) inside a dual-polarisation DDMZM (DPol-DDMZM). DDMZM$_\mathrm{X}$ is biased at the minimum transmission point (MITP), which generates two first order sidebands and a residual carrier with an amplitude determined by the modulator extinction ratio. The other DDMZM (DDMZM$_\mathrm{Y}$) is driven by two same-frequency sawtooth waves and is biased at the maximum transmission point (MATP). DDMZM$_\mathrm{Y}$ output polarisation state is rotated by 90° via a 90° polarisation rotator (PR). Thus, the optical signals in the two arms of the DPol-DDMZM have an orthogonal polarisation state.

They are combined by a polarisation beam combiner (PBC). The electric field at the output of the DPol-DDMZM can be obtained by modelling the DDMZM as two parallel connected optical phase modulators. It is given by

$$E_{\mathrm{DPol-DDMZM}}(t) = \begin{bmatrix} E_X(t) \\ E_Y(t) \end{bmatrix} = \frac{1}{2\sqrt{2}} E_{in}\sqrt{t_{ff}} e^{j\omega_c t} \begin{bmatrix} (1-\gamma)J_0(m_{RF}) + (1+\gamma)J_1(m_{RF})e^{j\omega_{RF}t} - (1+\gamma)J_1(m_{RF})e^{-j\omega_{RF}t} \\ \sum_{n=-\infty}^{\infty} a_n e^{j(n\omega_{saw}t+\theta_n)} + \gamma \sum_{m=-\infty}^{\infty} b_m e^{j(m\omega_{saw}t+\phi_m)} \end{bmatrix} \tag{1}$$

where E_{in} and ω_c are the amplitude and the angular frequency of the continuous wave light from a laser source into the DPol-DDMZM, t_{ff} is the insertion loss of the DDMZM, $\gamma = (\varepsilon^{1/2} - 1)/(\varepsilon^{1/2} + 1)$ is a scaling factor caused by the imbalanced amplitude between two arms of the DDMZM, ε is the DDMZM extinction ratio, $J_n(x)$ is the Bessel function of nth order of the first kind, $m_{RF} = \pi V_{RF}/V_\pi$ is the modulation index, V_{RF} is the amplitude of the input microwave signal into an RF port of the DDMZM, V_π is the half wave voltage of the phase modulator inside the DDMZM, ω_{RF} is the angular frequency of the input microwave signal and ω_{saw} is the angular frequency of the sawtooth wave, which is $2\pi/T_{saw}$ and T_{saw} is the sawtooth wave period. a_n, b_m, θ_n and ϕ_m are the amplitude and phase of the optical frequency components at $\omega_c + n\omega_{saw}$ and $\omega_c + m\omega_{saw}$ generated by the two phase modulators inside $\mathrm{DDMZM_Y}$ respectively. They are dependent on the amplitude and time delay of the sawtooth waves into the phase modulators. When a positive-slope sawtooth wave has an amplitude of $2V_\pi$ into a phase modulator, under an ideal situation, a perfect frequency translation with no loss is obtained [12]. That is $a_1 = b_1 = 1$ and $a_n = b_m = 0$ where $n \neq 1$ and $m \neq 1$. In practice, a sawtooth wave has a finite reset time and a nonlinear ramp segment, and a phase modulator has ripples in its frequency response. These non-ideal effects cause spurious signals to be present together with the frequency translated optical carrier at the phase modulator output. Therefore, the DPol-DDMZM output consists of a pair of the input microwave signal sidebands and a residual carrier from $\mathrm{DDMZM_X}$, and a frequency translated optical carrier and the spurious optical signals from $\mathrm{DDMZM_Y}$.

The two orthogonal linearly polarised optical signal at the DPol-DDMZM output pass through a linear polariser with an angle of 45° to the y-axis. This converts the two orthogonally linear polarised optical signals to have the same polarisation state. The upper microwave signal sideband is filtered out by an OBPF. The electric field of the frequency translator output optical signal can be expressed as

$$E_{out}(t) = \frac{1}{4} E_{in}\sqrt{t_{ff}} e^{j\omega_c t} \times \left[(1-\gamma)J_0(m_{RF}) - (1+\gamma)J_1(m_{RF})e^{-j\omega_{RF}t} + \sum_{n=-\infty}^{\infty} a_n e^{j(n\omega_{saw}t+\theta_n)} + \gamma \sum_{m=-\infty}^{\infty} b_m e^{j(m\omega_{saw}t+\phi_m)} \right] \tag{2}$$

The output optical signal is detected by a photodetector (PD). Beating of the frequency translated optical carrier and the lower microwave signal sideband at the PD generates a frequency translated microwave signal at an angular frequency of $\omega_{RF} + \omega_{saw}$. Its photocurrent amplitude can be obtained from (2) and is given by

$$I_{\omega_{RF}+\omega_{saw}} = -\frac{1}{8} P_{in} t_{ff} (1+\gamma) \left(a_1 e^{j\theta_1} + \gamma b_1 e^{j\phi_1}\right) J_1\left(m_{RF}\right) \Re \tag{3}$$

where P_{in} is the continuous wave light power into the DPol-DDMZM and $\Re$ is the PD responsivity. The photocurrents at the spurious signal angular frequencies of $\omega_{RF} + k\omega_{saw}$ where $-\infty < k < +\infty$ and $k \neq 1$ can also be obtained from (2). Note that the photocurrent at the original input microwave signal frequency is dependent on the modulator extinction ratio. We define the spurious suppression ratio to be the power ratio of the frequency translated microwave signal to the spurious signal that has the highest amplitude. Note that both $\mathrm{DDMZM_X}$ and $\mathrm{DDMZM_Y}$ are operated at the standard MITP and MATP respectively. Hence commercial modulator bias controllers (BCs) such as PlugTech MBC-MZM-01 can be used to avoid the bias drift problem.

In the second topology [Fig. 1(b)], a dual-parallel DDMZM (DP-DDMZM) is used instead of a DPol-DDMZM. The DP-DDMZM is formed by two sub-DDMZMs ($\mathrm{DDMZM_1}$ and $\mathrm{DDMZM_2}$) and a main MZM. Each MZM in the DP-DDMZM has a DC port, which enables the phase difference of the optical signals in the two arms of the MZM to be controlled by a DC voltage. An input microwave signal is applied to an RF port of $\mathrm{DDMZM_1}$ to modulate the light passing through the top phase modulator in $\mathrm{DDMZM_1}$. Therefore, the output of the top phase modulator consists of an optical carrier, and upper and lower microwave signal sidebands. A sawtooth wave is applied to the other RF port of $\mathrm{DDMZM_1}$. This shifts the frequency of the light passing through the bottom phase modulator in $\mathrm{DDMZM_1}$. $\mathrm{DDMZM_1}$ is biased at the MATP and its output electric field is given by

$$E_{DDMZM1}(t) = \frac{1}{2\sqrt{2}} E_{in}\sqrt{t_{ff}} e^{j\omega_c t}\left[J_0(m_{RF}) + J_1(m_{RF}) e^{j\omega_{RF} t} - J_1(m_{RF}) e^{-j\omega_{RF} t} + \gamma \sum_{n=-\infty}^{\infty} a_n e^{j(n\omega_{saw} t + \theta_n)}\right] \tag{4}$$

Each RF port of $\mathrm{DDMZM_2}$ is terminated by a 50 Ω terminator. The amplitude and phase of the optical carrier at $\mathrm{DDMZM_2}$ output can be controlled by the DC voltage V_{DC2} and V_{DC3} respectively. An OBPF is connected to the output of the DP-DDMZM to filter out the upper microwave signal sideband. The electric field of the frequency translator output optical signal can be expressed as

$$E_{out}(t) = \frac{1}{4} E_{in}\sqrt{t_{ff}} e^{j\omega_c t}\left[\left(1 + \gamma e^{j\alpha_2}\right) e^{j\alpha_3} + J_0(m_{RF}) - J_1(m_{RF}) e^{-j\omega_{RF} t} + \gamma \sum_{n=-\infty}^{\infty} a_n e^{j(n\omega_{saw} t + \theta_n)}\right] \tag{5}$$

where $\alpha_2 = \pi V_{DC2}/V_\pi$ and $\alpha_3 = \pi V_{DC3}/V_\pi$ are the bias angle of $\mathrm{DDMZM_2}$ and the main MZM respectively. The bias angles α_2 and α_3 can be designed so that the optical carriers in the two arms of the DP-DDMZM have the same amplitude but an opposite phase. Hence, the optical carrier is suppressed at the DP-DDMZM output. After photodetection, the amplitude of the photocurrent at the frequency translated microwave signal frequency can be obtained from (5) and is written as

$$I_{\omega_{RF}+\omega_{saw}} = -\frac{1}{8} P_{in} t_{ff} \gamma a_1 J_1(m_{RF}) \Re \tag{6}$$

The amplitude of the photocurrent at the original input microwave signal frequency can also be obtained from (5). It is given by

$$I_{\omega_{RF}} = -\frac{1}{8} P_{in} t_{ff} J_1(m_{RF}) \Re \sqrt{\left(\cos(\alpha_3) + \gamma\cos(\alpha_2+\alpha_3) + J_0(m_{RF}) + \gamma a_0\right)^2 + \left(\sin(\alpha_3) + \gamma\sin(\alpha_2+\alpha_3)\right)^2} \tag{7}$$

Assuming a sawtooth wave has a fall time to period ratio of less than 1%, which can be achieved by a commercial waveform generator. An over 44 dB spurious suppression ratio for a modulation index of less than 0.2 and a modulator extinction ratio of 35 dB can be obtained by setting the bias angles $\alpha_2 = 119.5°$ and $\alpha_3 = 122°$. This optimal bias angle setting has been confirmed using a photonic simulation software. In contrast to the DPol-DDMZM based frequency translator, the DP-DDMZM based frequency translator does not require any electrical component. It is an all-optical microwave frequency translator. Hence it has a wide bandwidth that is only limited by the DP-DDMZM bandwidth. However, $\mathrm{DDMZM_2}$ and the main MZM of the DP-DDMZM are biased away from the standard modulator operating points. Fortunately, a bias controller that has the ability to lock the DP-DDMZM operating point at an arbitrary point in the modulator transfer function has recently been reported [13]. Therefore, a large suppression in the optical carrier, which leads to a large spurious suppression ratio, can be maintained.

Note that both electronic and microwave photonic Serrodyne frequency translators [9]–[11], [14], [15] require a sawtooth wave. Since the frequency of the sawtooth wave determines the frequency translation rate, which is small for applications such as velocity deception in ECM systems, a commercial low-cost waveform generator can be used to generate a sawtooth wave with frequencies up to few MHz and around 1% fall time to period ratio. As with all microwave photonic signal processors, the cost for implementing a frequency translator using microwave photonic techniques is higher than electronic techniques. However, microwave photonic frequency translators can be designed to have wide operating frequency range and large spurious suppression ratio that cannot be achieved by its electronic counterpart. It should be emphasised that using the conventional microwave photonic mixers or frequency converters [15], [16] for frequency translation has the problem of the carrier and sidebands being present at the frequency translator output, which interfere with the frequency translated signal. There are few reports on microwave photonic based single sideband (SSB) mixers [17], [18] in which the carrier and sidebands are suppressed. However, they are unable to realise frequency translation with $>$35 dB spurious signal suppression and have a complex structure.

3. Experimental Results

Experiments were set up to verify the principle for the new topologies described above. A wavelength tunable laser (Santec WSL-100) operating at 193.43 THz and 10 dBm was used as an optical source. The light generated by the laser source was launched into a DPol-DDMZM (Fujitsu FTM7980EDA) via a polarisation controller. A 12 GHz microwave signal from a microwave signal generator passed through a 1-18 GHz bandwidth 180° hybrid coupler before applying to DDMZM$_{\mathrm{X}}$ in the DPol-DDMZM. Two sawtooth waves generated by a dual-output waveform generator (Rigol DG4102) were separately fed to each RF port of DDMZM$_{\mathrm{Y}}$. DDMZM$_{\mathrm{X}}$ and DDMZM$_{\mathrm{Y}}$ were biased at MITP and MATP respectively. An in-line polariser with a 45° angle was connected to the DPol-DDMZM output. This was followed by a tunable optical filter (Alnair Lab BVF-300CL). An erbium-doped fibre amplifier (EDFA) was employed to compensate for the system loss. A tunable optical filter with a 0.5 nm 3-dB bandwidth was connected to the EDFA output. It was used to suppress the amplified spontaneous emission noise. The output optical signal was detected by a PD, whose output was connected to an electrical signal analyser (ESA) to display the system output electrical spectrum. The microwave signal generator, the waveform generator and the ESA were synchronised using a common 10 MHz reference signal.

The amplitudes of the two same-frequency sawtooth waves were set to be around 5.4 V, which is twice the DPol-DDMZM half wave voltage. The phase of one of the sawtooth waves was fixed at 0° while the other was adjusted to obtain large spurious signal suppression. Fig. 2 shows the DPol-DDMZM based frequency translator output electrical spectrums for different-frequency sawtooth waves into DDMZM$_{\mathrm{Y}}$. As can be seen from the figure, the input microwave signal is translated from 12 GHz to 12 GHz + 500 Hz, 12 GHz + 10 kHz, 12 GHz + 1 MHz, and 12 GHz + 3 MHz. The frequency translation rate is the same as the sawtooth wave frequency. The frequency translated microwave signal amplitude remains the same as the frequency translation rate varies. The frequency translator spurious suppression ratio for the four different-frequency translation rates are 36.1 dB, 43.5 dB, 42.9 dB and 35.8 dB. Over 35 dB spurious suppression ratios for frequency translation rates other than that shown in Fig. 2 but between 500 Hz and 3 MHz, were also measured. Note that the spurious suppression ratio reduces at a small 500 Hz and a large 3 MHz frequency translation rate. This spurious suppression ratio reduction was investigated. It was found that the fall time to period ratio of the sawtooth wave generated by the waveform generator increases as the sawtooth wave frequency increases. The fall time to period ratio is larger than 1% for a 3 MHz sawtooth wave, which results in a less than 40 dB spurious suppression ratio according to the simulation result given in [19]. Reduction in the spurious suppression ratio for a small frequency translation rate of 500 Hz was found to be due to the ramp segment of the sawtooth wave generated by the waveform generator is less linear as the frequency of the sawtooth wave reduces.

The frequency translator output in the time domain was examined. Due to the lack of a high frequency oscilloscope, the output of the PD was connected to a mixer (Minicircuits ZX05-24MH-S +) to down convert the frequency translated microwave signal at 12 GHz + 10 kHz to 10 kHz. The 10 kHz waveform at the mixer output was measured on an oscilloscope (Keysight DSOX2014A)

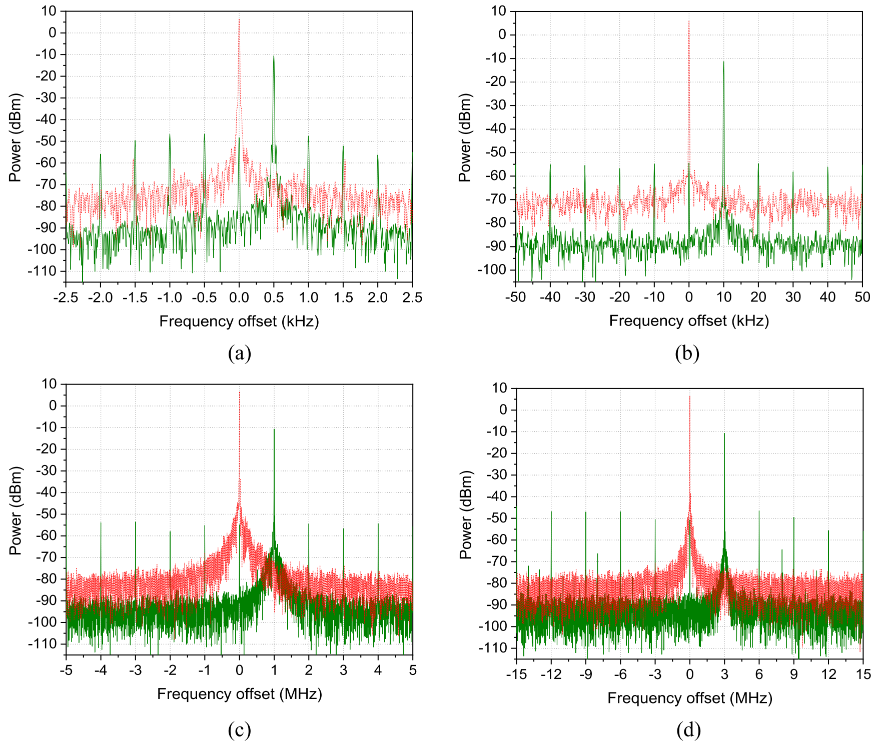


Fig. 2. DPol-DDMZM based frequency translator output electrical spectrum (green line) for sawtooth waves with a frequency of (a) 500 Hz, (b) 10 kHz, (c) 1 MHz and (d) 3 MHz, into DDMZM$_{\mathrm{Y}}$. Electrical spectrum (red dashed line) of the 12 GHz microwave signal into DDMZM$_{\mathrm{X}}$.

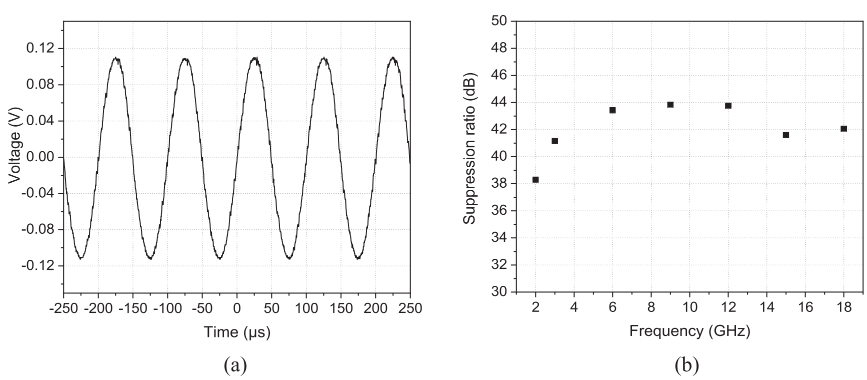
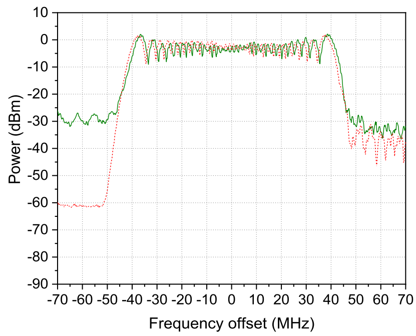
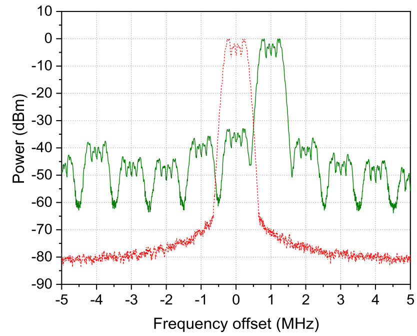


Fig. 3. (a) Waveform of the 12 GHz + 10 kHz frequency translated microwave signal after down converted to 10 kHz via a mixer. (b) Spurious suppression ratio of the DPol-DDMZM based frequency translator operating at different input microwave signal frequencies.

and is shown in Fig. 3(a). This shows there is no perturbation to the time domain waveform. The DPol-DDMZM based frequency translator spurious suppression ratio was measured for different input microwave signal frequencies from 2 GHz to 18 GHz. The frequency of the sawtooth wave was fixed at 1 MHz. The experimental result, shown in Fig. 3(b), demonstrates the proposed structure is capable to realise microwave signal frequency translation with a high spurious suppression ratio of more than 38 dB over a wide input microwave signal frequency range. The lower operating frequency is limited by the edge roll-off of the tunable optical filter used for removing



(a)



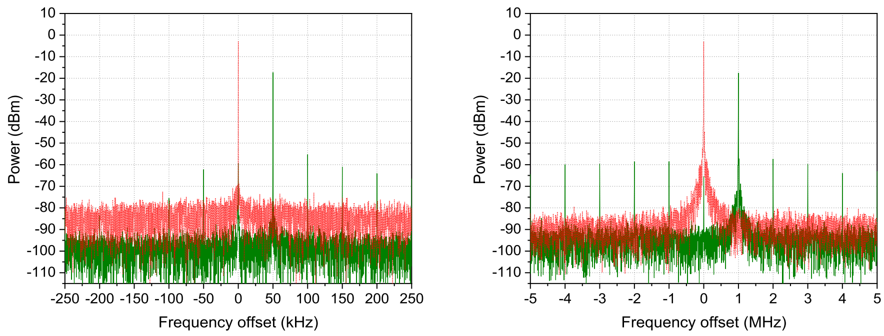
(b)

Fig. 4. Electrical spectrum of a FMCW signal at 5.88 GHz into the DPol-DDMZM based frequency translator (red dashed line) and frequency translator output electrical spectrum (green line) when the FMCW signal has a (a) 40 MHz and (b) 200 kHz frequency deviation.

one microwave signal sideband. The frequency translator output stability was investigated. It was found that the amplitude of the spurious signal at 12 GHz was gradually increased with time. This is mainly due to the bias drift problem causing $\mathrm{DDMZM_X}$ operating away from the MITP. Commercial modulator bias controllers need to be incorporated with the frequency translator to lock the two DDMZM bias points in order to obtain a long-term stable performance. Nevertheless, more than 34 dB spurious suppression ratio can be maintained over 30 minutes without adjusting the modulator bias voltages.

Until now, all microwave photonic frequency translators and most electronic frequency translators reported in literatures only demonstrate frequency translation of a single-frequency microwave signal. In practice, a microwave signal has a band of frequency. The bandwidth of the microwave signal into the frequency translator is normally larger than the frequency translation rate. Therefore the carrier and sidebands are located within the frequency translated signal bandwidth. In order to ensure the carrier and sidebands have negligible effect on the frequency translated signal so that the bandwidth of the input microwave signal is not limited by the frequency translation rate or the sawtooth wave frequency, a large spurious suppression ratio is needed. A frequency modulated continuous wave (FMCW) signal was applied to the DPol-DDMZM based frequency translator to investigate its performance when frequency translating a microwave signal with a band of frequency. The FMCW signal was generated by a waveform generator (Keysight 33621A). It had 80 MHz carrier frequency, 40 MHz frequency deviation and 800 kHz frequency modulation frequency. It was upconverted to 5.88 GHz by mixing with a 5.8 GHz LO using a 6 GHz bandwidth mixer (Marki T3-06LQP). The frequency of the sawtooth wave into the frequency translator was 1 MHz. Fig. 4(a) shows the DPol-DDMZM based frequency translator input and output spectrum. Note that the amplitude of the input and output spectrum were normalised so that a 1 MHz frequency translation can be clearly seen by comparing the input and output spectrum. Since the FMCW signal has a bandwidth of twice the frequency deviation, i.e., 80 MHz, the carrier and sidebands are located within the frequency translated signal bandwidth. Hence the spurious suppression ratio cannot be measured. To demonstrate frequency translation of a microwave signal with a band of frequency, at the same time measuring the spurious suppression ratio, the frequency deviation of the FMCW signal was reduced to 200 kHz. Fig. 4(b) shows the spurious suppression ratio is more than 34 dB. This demonstrates a large spurious suppression ratio can be obtained even when the proposed structure is used for frequency translating a microwave signal with a band of frequency.

The DPol-DDMZM and the in-line polariser were replaced by a DP-DDMZM (Fujitsu FTM7960EX) to verify the second microwave photonic frequency translator topology. A 10 GHz microwave signal and a sawtooth wave were applied separately to the two RF ports of $\mathrm{DDMZM_1}$ inside the DP-DDMZM. $\mathrm{DDMZM_1}$ was operated at the MATP. The RF ports of $\mathrm{DDMZM_2}$ were terminated by 50 Ω terminators. The laser, the tunable optical filters, the EDFA and the PD used



(a) (b)

Fig. 5. DP-DDMZM based frequency translator input (red dashed line) and output (green line) electrical spectrum for a sawtooth wave with a frequency of (a) 50 kHz and (b) 1 MHz, into DDMZM$_1$. The frequency translator input microwave signal frequency is 10 GHz.

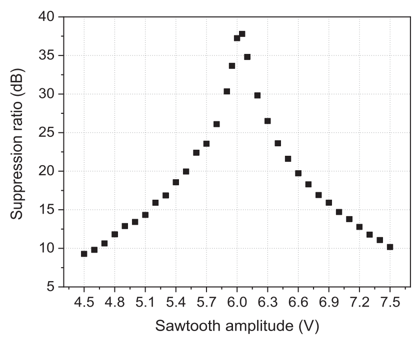


Fig. 6. DP-DDMZM based frequency translator spurious suppression ratio versus the sawtooth wave amplitude.

in the experiment were the same as that used in the DPol-DDMZM based frequency translator experiment. Fig. 5 shows the frequency translator output spectrum after adjusting the bias voltages into DDMZM$_2$ and the main MZM of the DP-DDMZM to suppress the spurious signal at the original input microwave signal frequency. The amplitude of the sawtooth wave was adjusted to minimise the amplitudes of the spurious signals at other frequencies. The optimal sawtooth wave amplitude was 6.05 V. The experimental results show a large spurious suppression ratio of 38.1 dB and 39.8 dB for a frequency translation rate of 50 kHz and 1 MHz respectively. The effect of changing the sawtooth wave amplitude on the spurious suppression ratio was investigated. Fig. 6 shows the DP-DDMZM based frequency translator spurious suppression ratio for different sawtooth wave amplitudes between 4.5 V and 7.5 V. It can be seen from the figure that the spurious suppression ratio reduces as the sawtooth wave amplitude moves away from 6.05 V. In theory, the sawtooth wave amplitude needs to be twice the half wave voltage of the phase modulator inside the DDMZM in order to minimise the spurious signal amplitudes. This shows the modulator half wave voltage is around 3 V, which agrees with that given in the modulator specification.

4. Conclusion

Two new microwave photonic frequency translators have been presented. They are based on a DPol-DDMZM or a DP-DDMZM, followed by an OBPF. Microwave signal frequency translation is realised by beating of a frequency translated optical carrier with a microwave signal sideband at a PD. The DPol-DDMZM based frequency translator can achieve a very large spurious suppression ratio by optimising the amplitude and the time delay difference of two same-frequency sawtooth waves into the modulator to compensate for the non-ideal effects present in the Serrodyne frequency translation process. The DP-DDMZM based frequency translator is free of electrical components, which has the potential to operate over a very wide frequency range that is only limited by the modulator bandwidth. Spurious suppression ratio of 43.5 dB and 39.8 dB have been demonstrated using the DPol-DDMZM based frequency translator operating at 10 kHz translation rate and the DP-DDMZM based frequency translator operating at 1 MHz translation rate respectively. Frequency translation of a microwave signal with a band of frequency has also been demonstrated for the first time using a microwave photonic technique. The new microwave photonic frequency translators can find applications in electronic warfare and communication.

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