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Optical frequency comb optimization for satellite payload applications based on multitone phase modulation

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ABSTRACT

We investigate the generation and shape manipulation of an optical frequency comb (OFC) by using a phase modulator (PM) driven by multiple RF signals. The rationale is to use the OFC to act as the light source of dense wavelength division multiplexing (DWDM) or to achieve photonically-assisted mm-wave generation, e.g., 15 GHz – 60 GHz (Ka/V IEEE bands) and to be able to integrate these key functionalities onto satellite payloads.

We propose to externally modulate a narrow-linewidth continuous wave (CW) laser using an electro-optic phase modulator driven by multiple RF signals. The shape of the comb can be controlled by setting the frequencies, the amplitudes and the relative phases of the driving signals. Consequently, we can attenuate the undesired frequencies leaving just two tones whose frequency difference is equal to the desired mm-wave. In this work, we present an extinction ratio between the two desired tone and the strongest undesired one of approximately 10 dB. Heterodyne detection with a photodiode generates the mm-wave signal. Moreover, controlling the OFC shape allows the generation of an ultra-flat OFC. We present an OFC of 13 lines and 3 GHz spacing showing an amplitude difference between the strongest and weakest line of 0.5 dB.

This technique avoids the use of an intensity modulator, exploiting the good insertion loss performance of the PM, shows good power efficiency and is extremely simple and cheap with respect to other OFC generation techniques such as mode-locked lasers.

Keywords: Optical frequency comb, flat-comb generation, mm-wave generation, multitone phase modulation, phase modulation, optical comb optimization, flat optical comb, continuous-wave (CW) modulation.

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1. INTRODUCTION

Satellite communications (SATCOM) have experienced significant growth in recent years. In particular, the demand for Tbps throughputs is pushing the frequency generation units (FGU) of satellite payloads towards Ka, Q/V and W-band frequencies, with a market $ 19.4 billion by 2028 [1]. Besides high operating frequencies, the other main requirements to be addressed when dealing with satellite payloads are low mass and size, low power consumption and high flexibility. Traditional payloads based on RF equipment require an increased complexity, higher size, weight and power consumption when dealing with higher frequencies and payload reconfigurability [2]. Even dielectric resonators, which are the most promising technique in conventional microwave oscillators, experience a dramatic quality factor decrease moving towards Ka/V/W bands. Photonics represents a promising way to address the aforementioned issues [2]. In particular, optical frequency comb generation is a convenient approach to generate phase correlated and accurately spaced optical lines. At this point the optical comb can serve many applications such as DWDM, in which it operates as the light source, and for the generation of mm-waves by heterodyning (by selecting two lines out of the comb and making them beat onto a photodiode). Considering the former application, it is important to ensure high comb flatness, so that the channels share the same amount of power. In the latter case, instead, it is important that the extinction ratio between the selected and the suppressed tones is as high as possible.

Many different OFC generation techniques have been developed. Mode-locked lasers (MLL) can provide OFC at high bandwidth and high stability, however this is at the cost of a limited tunability in terms of frequency spacing and center wavelength, high costs and design complexity [3][4]. Another approach which is largely used to generate OFC is the external modulation of a CW laser [5]. Many works have been published employing more than one modulator, both phase and intensity modulators, connected in different topologies in series or parallel. All these approaches guarantee large comb spacing and center wavelength tunability together with a good stability of the output. However, it is clear that increasing the number of modulators also increases complexity and losses of the system. Moreover, it is to be noted that using intensity modulators will lower the efficiency of the system, being based on modulating loss rather than the frequency of the input light [6], [7] and [8]. Ozharar *et al.* have proposed in [6] a way to generate an ultra-flat frequency comb by using a single-phase modulator driven by two RF signals whose frequencies were harmonically related. In this way, they have generated an optical comb made up of 11 tones spaced by 3 GHz and showing an amplitude variation, here also called flatness, of about 1.3 dB.

The aim of this work is to extend this approach by driving the phase modulator with multiple harmonically related RF signals. Besides improving the comb flatness, focus is given to studying the comb-shape manipulation that can be obtained by using this multitone phase modulation strategy. Here, we present an OFC of 13 lines and 3 GHz spacing showing an amplitude difference of 0.5 dB between the strongest and weakest line. We also generated an OFC of 11 lines and 3 GHz spacing having an amplitude difference lower than 0.5 dB. Finally, we modified the input driving signals to achieve a heterodyne signal with an extinction ratio of about 10 dB between the two desired tones and the strongest undesired one.

2. THEORY OF MULTITONE PHASE MODULATION

The output of a phase modulator driven by a single RF signal can be expressed by the Jacobi-Anger expression as shown in Eq. (1) [9]:

$$E_{in} e^{i \cdot A \cdot sin(\omega_m t)} = E_{in} \sum_{n=-\infty}^{+\infty} J_n(A) \cdot e^{i \cdot n \cdot \omega_m t}. \tag{1}$$

In Eq. (1), $A \cdot sin(\omega_m t)$ is the sinusoidal driving signal having a modulation angular frequency, ω_m, and an amplitude, also known as modulation depth, E_{in} is the scalar input electric field and J_n is the Bessel function of first kind and order n evaluated in A. From a physical perspective, Eq. (1) shows that the phase modulator output field can be expressed as an infinite summation of sinusoidal signals whose frequencies $n\omega_m$ are integer multiples of the modulating frequency (i.e. harmonics), and whose amplitudes are given by $J_n(A)$. For the sake of clarity, the absolute values of amplitudes of the first three harmonics are plotted in Fig. 1.

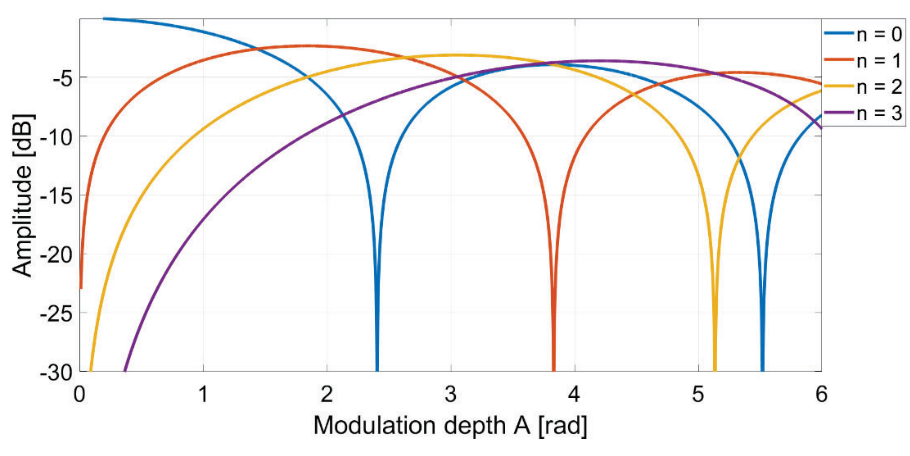

Fig. 1. Amplitudes of the first three harmonics in absolute value and logarithmic scale. Because of the Bessel function symmetry, the amplitude of the nth harmonic is equal to the amplitude of the -nth, where *n* is the harmonic order.

There are several observations to be inferred from Fig. 1. Firstly, when $A = 0$, (i.e., no phase modulation), there is no harmonic generation, therefore the amplitudes tent to $-\infty$ for every value of n apart from $n = 0$, which is the frequency of the optical carrier. In addition to that $|J_n(A)| = |J_{-n}(A)|$, because of the well-known Bessel function symmetry property. This allows us to plot only the positive values of n, as the negative values would give exactly the same plot. Finally, it is to be noted that there is no value of A for which all the different curves intersect; thus, it is not possible to attain a perfectly flat comb. Moreover, it can be proved that when considering A in the interval [0-6], no spectrum with a flatness better than 3 dB can be obtained, independently of the parameter A.

Ozharar *et al.* [6] proposed to improve the flatness of the OFC by simultaneously driving the phase modulator with two RF signals. By using frequencies at 3 GHz and 9 GHz with respective modulation depths of 5.13 and 2.49 and a zero-phase difference, an OFC with 11 lines and a flatness of 1.3 dB was produced [6]. In this work, we consider the most general case in which the phase modulator is driven by the sum of an arbitrary number of sinusoids potentially having different amplitudes, phases and frequencies, given that all the driving frequencies are integer multiples of the modulating one. Specifically, we analyze the case in which the phase modulator is driven by the sum of three sinusoids and derive the governing equations of the harmonic amplitudes when the number of RF driving signals is 4 as well as the generalized equation for k signals, where k is an integer. We find that the OFC can be optimized for flatness by engineering the amplitudes, frequencies and phases values. In the case of three driving signals, we have at the PM electrical input the sum of three sine waves: $A\cdot sin(\omega_m t+\Delta\phi_1)+B\cdot sin(p\cdot\omega_m t+\Delta\phi_2)+C\cdot sin(q\cdot\omega_m t)$.

A, B, C are the amplitudes, ω_m, $p\omega_m$ and $q\omega_m$ are the modulating angular frequencies, where p and q are integers, $\Delta\varphi_1$ and $\Delta\varphi_2$ are the phase differences between the respective signals and the signal chosen as a phase reference, in this case the third one. The equation governing the amplitudes of each harmonic of the OFC is:

$$\begin{aligned}
&E_{in}e^{i\cdot\left[A\cdot sin(\omega_m t+\Delta\phi_1)+B\cdot sin(p\cdot\omega_m t+\Delta\phi_2)+C\cdot sin(q\cdot\omega_m t)\right]}=\\
&=E_{in}\left[\sum_{k=-\infty}^{+\infty}J_k(A)\cdot e^{i\cdot k\cdot(\omega_m t+\Delta\phi_1)}\right]\cdot\left[\sum_{h=-\infty}^{+\infty}J_h(B)\cdot e^{i\cdot h\cdot(p\cdot\omega_m t+\Delta\phi_2)}\right]\cdot\left[\sum_{l=-\infty}^{+\infty}J_l(C)\cdot e^{i\cdot l\cdot q\cdot\omega_m t}\right]=\\
&=E_{in}\sum_{n=-\infty}^{+\infty}\left[\sum_{h=-\infty}^{+\infty}J_h(B)\cdot\left(\sum_{l=-\infty}^{+\infty}J_l(C)\cdot J_{n-hp-lq}(A)\cdot e^{i\cdot(n-hp-lq)\cdot\Delta\phi_1}\right)\cdot e^{i\cdot h\cdot\Delta\phi_2}\right]\cdot e^{i\cdot n\cdot\omega_m t}.
\end{aligned}\tag{2}$$

In Eq. (2), we recognize the same structure observed in Eq. (1). The outermost complex exponential indicates the frequency position of the harmonics making up the OFC, while its amplitude is given by the complex expression contained in the outermost parenthesis. It is clear that instead of having a single Bessel function evaluated in A as in Eq. (1), we have many more degrees of freedom here, namely A, B, C, p, q, $\Delta\varphi_1$ and $\Delta\varphi_2$. This allows a performance improvement in terms of comb flatness. For the sake of clarity, we also report in Eq. (3) the governing equation of harmonic amplitudes for the case of a PM driven by 4 RF signals.

$$\begin{aligned}
&E_{in}e^{i\cdot\left[A\cdot sin(\omega_m t+\Delta\phi_1)+B\cdot sin(p\cdot\omega_m t+\Delta\phi_2)+C\cdot sin(q\cdot\omega_m t)+D\cdot sin(r\cdot\omega_m t+\Delta\phi_3)\right]}=\\
&=E_{in}\sum_{n=-\infty}^{+\infty}\left\{\sum_{z=-\infty}^{+\infty}J_z(D)\cdot\left[\sum_{h=-\infty}^{+\infty}J_h(B)\cdot\left(\sum_{l=-\infty}^{+\infty}J_l(C)\cdot J_{n-hp-lq-rz}(A)e^{i\cdot(n-hp-lq-rz)\cdot\Delta\phi_1}\right)\cdot e^{i\cdot h\cdot\Delta\phi_2}\right]\cdot e^{i\cdot z\cdot\Delta\phi_3}\right\}\cdot e^{i\cdot n\cdot\omega_m t}.
\end{aligned}\tag{3}$$

Equations (2) and (3) can be generalized for the general case with an arbitrary number of RF driving signals, k, as follows:

$$
\begin{aligned}
& E_{in} e^{i\cdot\left[A_1\cdot sin\left(\omega_m t+\Delta\phi_1\right)+A_2\cdot sin\left(p_1\cdot\omega_m t+\Delta\phi_2\right)+\ldots+A_k\cdot sin\left(p_{k-1}\cdot\omega_m t\right)\right]} = \\
& = E_{in}\sum_{n=-\infty}^{+\infty}\left\{\sum_{q_{k-1}=-\infty}^{+\infty} J_{q_{k-1}}\left(A_{k-1}\right)\cdot\left[\sum_{q_{k-2}=-\infty}^{+\infty} J_{q_{k-2}}\left(A_{k-2}\right)\cdots\right.\right. \\
& \left.\left.\cdots\left(\sum_{q_k=-\infty}^{+\infty} J_{q_k}\left(A_k\right)\cdot J_{n-p_1q_2-p_2q_3-\ldots-p_{k-1}q_k}\left(A_1\right)\cdot e^{i\cdot\left(n-p_1q_2-p_2q_3-\ldots-p_{k-1}q_k\right)\cdot\Delta\phi_1}\right)\cdot e^{i\cdot q_2\cdot\Delta\phi_2}\right]\cdots e^{i\cdot q_{k-1}\cdot\Delta\phi_{k-1}}\right\}\cdot e^{i\cdot n\cdot\omega_m t} \qquad (4)
\end{aligned}
$$

3. SIMULATION RESULTS

3.1 Flat OFC generation

Simulations were performed with three RF input signals to the phase modulator. As mentioned in Section 2, in this case the degrees of freedom are represented by A, B, C, p, q, $\Delta\varphi_1$ and $\Delta\varphi_2$, once ω_m is chosen. We started by optimizing the comb flatness, which means generating an OFC having the highest number of lines possible, where the amplitude difference between the strongest line and the weakest one is minimized. We have written code in MATLAB, which computes the optimum condition for a comb made up of 13 lines, whose frequency spacing between the different tones was 3 GHz. The code implements Eq. (2). It was found that the optimum condition is achieved for $A = 6$, $B = 0.54$, $C = 0.66$, $\Delta\varphi_1 = \pi/6$, $\Delta\varphi_2 = 0$, $p = 5$ and $q = 3$. For these input values, an amplitude variation of 0.5 dB was obtained between the strongest and the weakest lines of the comb. We computed also the optimum inputs to generate an OFC with 11 lines by driving the PM with 3 signals ($A = 2.06$, $B = 5.44$, $C = 5.56$, $\Delta\varphi_1 = \pi/6$, $\Delta\varphi_2 = 0$, $p = 5$ and $q = 3$). In this latter case the amplitude variation was lower than 0.5 dB. On the other hand, the optimum condition for a 13 lines OFC with 3 GHz frequency spacing when only two driving signals are applied to the modulator produces an amplitude variation of 1.6 dB (optimum inputs are; $A = 1.4$, $B = 4.48$, $\Delta\varphi_1 = \pi/2$, $p = 3$). To have a deeper insight into how the input parameters affect the final flatness, we show in Fig. 2 and Fig. 3 the variation of the first 6 harmonics as a function of $\Delta\phi_1$ and B, respectively. It is to be noted that being all the input frequencies odd multiples of ω_m the amplitude of the -nth harmonic is equal to the amplitude of the -nth one that is the spectrum is symmetrical with respect to the y axis as shown in Fig. 4. This is not true when all the frequencies are even multiples of ω_m or in the most general case where p and q are arbitrary indices. In these last cases, the amplitude of each single harmonic should be computed per se.

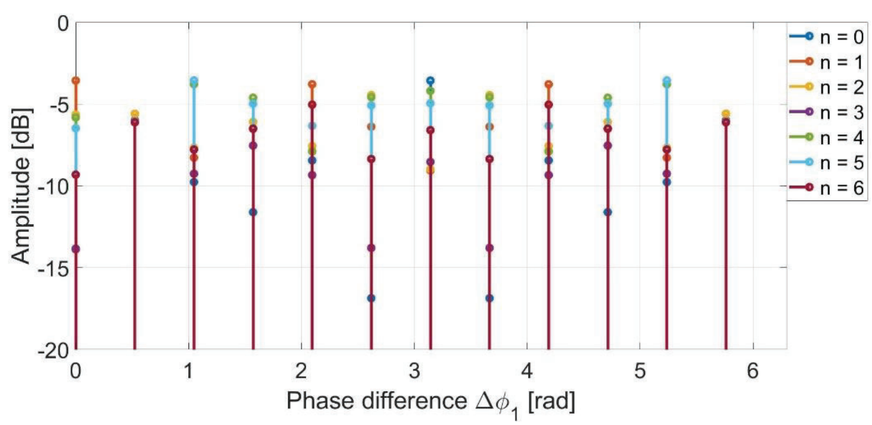

Fig. 2. Amplitude of the first six harmonics as a function of the phase difference between the first signal and the signal chosen as phase reference. The value of 'n' indicates the considered sideband.

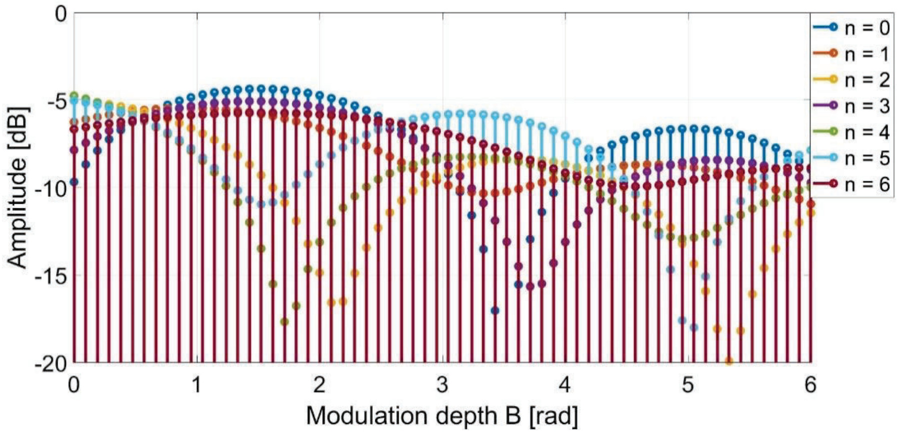

Fig. 3. Amplitude of the first six harmonics as a function of the modulation depth of the second sinusoidal signal. The value of 'n' indicates the considered sideband.

Looking at Fig. 3, we can see that the harmonics amplitudes show a smooth behavior with $\Delta\varphi_1$ and that the value for the optimum flatness must be around π/6 as all the harmonics tend to converge to the same amplitude value. In contrast, when looking at $\Delta\varphi_1 \approx 5\pi/6$, flatness is at its minima being the harmonics amplitude values significantly divergent. A similar analysis can be done for Fig. 4 where the amplitudes of the harmonics converge to a value of B close to 0.5, as expected from the optimum values mentioned above.

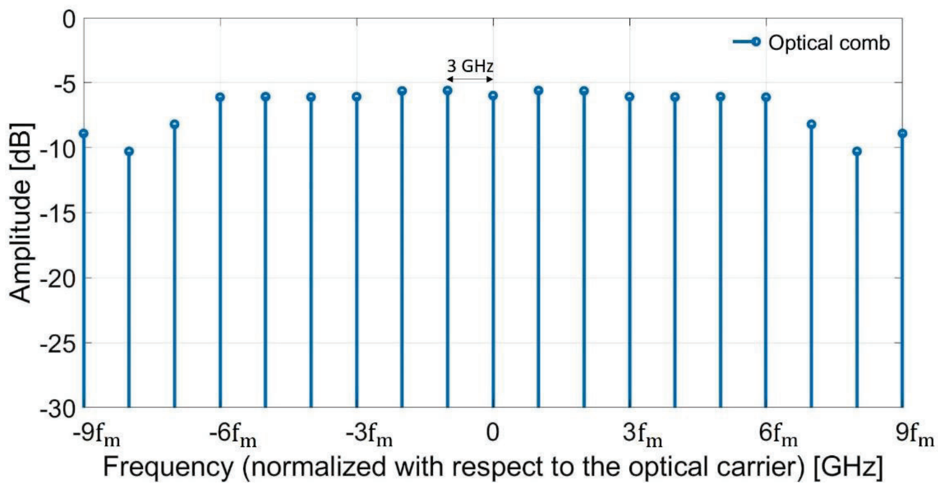

Fig. 4. Output spectrum showing the generated ultra-flat 13 lines and 3 GHz spacing OFC. The amplitude difference between the strongest and the weakest line of the comb is 0.5 dB.

The optimum values for amplitudes, frequency and phase differences found before allow the generation of a 13 lines OFC with 3 GHz line spacing having an amplitude difference of 0.5 dB. If considering just a 11 lines OFC always keeping 3 GHz line spacing with its respective optimum inputs, the amplitude difference reduces to less than 0.5 dB. The respective optimum amplitude variations when driving the PM with just two sinusoids are 1.6 dB and 1.3 dB. A comparison of the combs generated by two driving signals and 3 driving signals is given in Fig. 5. For the sake of clarity, we plotted just the 13 peaks of the amplitude in the two cases. The red circles corresponding to the three driving voltages show a flatter trend as expected.

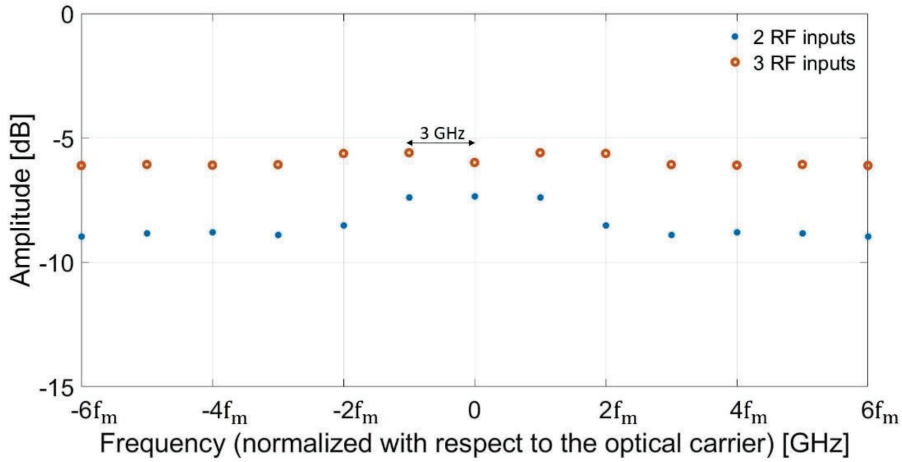

Fig. 5. Comparison between the 13 lines output OFC when driving the PM with two or three RF signals. The spacing is set to 3 GHz in both cases and the amplitude difference is 1.6 dB and 0.5 dB, respectively.

3.2 Heterodyne signal generation

The aim of this part of the work is to use the PM driven by three RF sinusoids to generate a mm-wave. The rationale is to create an OFC in which we attenuate all the undesired frequency components, leaving just two tones whose frequency difference is equal to the desired mm-wave output. Heterodyne detection with a photodiode generates the desired mm-wave signal. We have focused on a 60 GHz FGU, given the emerging interest in the W-band. As in the comb flatness case, we use as driving frequencies f_m = 3 GHz, pf_m = 15 GHz and qf_m =9 GHz. To find the other input, we imposed that the extinction ratio (ER) between the desired tones and the strongest undesired tone was at least 10 dB. We found that A = 3.98, B = 4.31, C = 1.30 and $\Delta\varphi_1 = \Delta\varphi_2 = 0$ satisfy this condition. These values can be further optimized improving the extinction ratio and therefore the quality of the RF output signal. The obtained output is shown in Fig. 6.

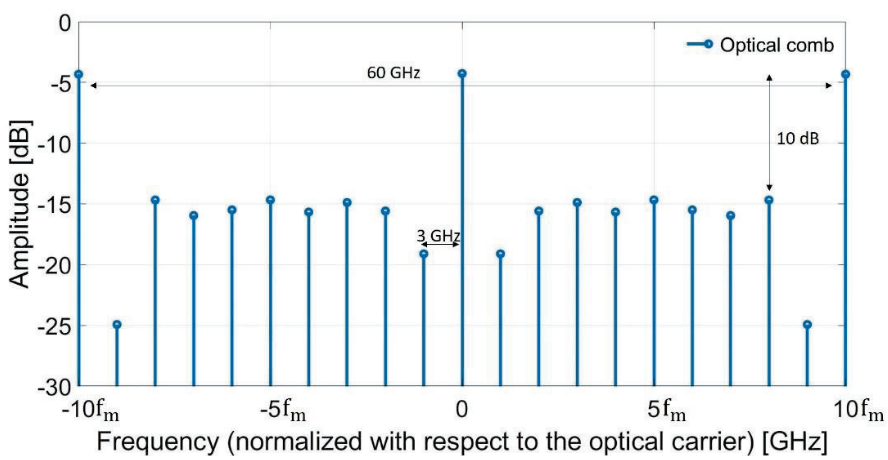

Fig. 6. Heterodyne output signal generated by driving the modulator with three RF signals. The extinction ratio between the desired tones and the undesired ones is always higher than 10 dB.

4. CONCLUSION

Multitone phase modulation provides an effective tool to optimize OFCs. For example, by driving a PM with three sinusoidal signals it is possible to generate an OFC with 13 lines in which the line spacing is 3 GHz and the amplitude difference between the strongest and the weakest comb line is 0.5 dB. Also, a spectrum of 11 comb lines with 3 GHz spacing and less than 0.5 dB amplitude difference was generated. Finally, a heterodyne signal was obtained in which the two desired tones have a spacing of 60 GHz and the extinction ratio between the desired lines and the strongest undesired one is greater than 10 dB.

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