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Designing an optical frequency comb generator for visible light communication applications

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ABSTRACT

The optical frequency comb generator (OFCG) is an efficient optoelectronic device that is included in many important applications over a various field such as microwave and optical communication. A novel scheme of OFCG presented in this work for visible light communication application based on amplitude modulation, radio frequency (RF) signal, phase shift and two Mach-Zehnder modulators (MZMs), our design features are simple with more efficient power and premium flatness of comb lines, the number of generating frequencies lines was 64 with a power stronger than -2 dBm over a 340 GHz bandwidth from a single continuous laser diode. Different chirping factor (α) of MZMs are implemented (3, 5, 7), as the results the best results related to α=5 with extra flatness, the system was designed and simulated by VPI design suite 9.8.

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1. INTRODUCTION

Optical frequency comb generator (OFCG) is a vital component source for many applications based on multi-wavelength sources such as optical frequency measurement, optical frequency division multiplexing (OFDM), microwave photonic signal processing, optical arbitrary waveform generation and dense wavelength division multiplexing [1]-[3]. the basic principle of OFCG is to generate a set of optical signals or harmonics from a single optical source with maximum exploitation of the optical bandwidth, the spacing between these harmonics is tunable [4], [5]. Can benefit of OFCG by reducing the optical sources in the optical line terminal (OLT) side with providing broad bandwidth and high transmission data rate [6].

The key characteristics of OFCG are equal frequency spacing between lines, optical spectrum flatness, the narrow linewidth of each comb line, low implementation cost and wide spectrum wavelength range [2], [6], [7]. Many different techniques were presented by many researchers over the last years each one has its merits and demerits, these techniques were categorised into two methods, electrical and optical, the electrical one was limited by the bandwidth of the electrical components while the optical method allowed broader bandwidth, therefore the optical method is the most prevalent in the researches nowadays [7], [8]. For the optical method, one technique to implementation OFCG by using mode-locked laser (MLL) such as in [8]-[10], the mean disadvantages of this method are the stability and its hard to tunable the spacing between lines, because of the carrier frequency depending on the cavity of the laser diode due to the environments, for stable operation, it required a complicated feedback loop for stable operation [11], [12].

Another technique is based on fiber nonlinearity, such as the four-wave mixing effect (FWM) and stimulated brillouin scattering (SBS), this technique characterized by complex structure and required high power optical amplifiers and optical filter to sort the optical spectrum [1]-[3], [7], [13]. The most common and efficient technique is the optical modulation technique, which's based on optical modulation of the narrow internal or external seed source to produce multiple wavelengths or frequency comb lines by using single or multiple modulators with nested, cascaded or loop structures [6]. This method characterized by stability easy tunable comb spacing and flexibility [1], [14], [15].

Modulating the continuous wave (CW) diode can be performed using a single modulator, the system will be simple and generated a limited number of comb lines [10], [11], [16]. To increase the number of comb line, cascaded scheme of modulator were presented. This technique restricted by the insertion losses of the optical modulator which limits the bandwidth [6], [17].

Another important technique is ring or loop structure, called recirculating frequency shifting (RFS). This technique is more efficient than modulation technique in the term of bandwidth [6], [18]-[20], it implemented by different ways in many researchers as explained in next section. In this work, we proposed a novel scheme for visible light communication (VLC) application such as light fidelity (Li-Fi) based on CW laser, amplitude modulation (AM), two Mach-Zehnder modulators, phase shift. The chirping factor of Mach–Zehnder modulators (MZMs) was varied with three different values (α=3, 5, 7) and compare the results to study the effect of the chirping factor on the flatness of the comb generator output. We obtained 64 comb line with very good optical power and an excellent level of flatness over 340 GHz bandwidth.

2. LETRECHER REVIEW

We classified the previous works based on the techniques that were used to implemented OFCG. For the MLL technique, the centre frequency is fixed by the design of laser and spaced comb line determined by laser cavity length [6], [21]. Mode locked laser diode (MLLD) structure can be linear or ring cavity structures. Harvey and Mollenauer [12], Shan and Spirit [13], and Kato *et al.* [14] employ loop of optical fiber and comb generator equipped with a Fabry-Perot light modulator, in this method the frequency intervals are precisely constant and fixed phase rotation between spectrum components. This method is unstable due to fluctuation of the path so this method required a more complicated stabilization system [15]. Kawanishi *et al.* [15] designed OFCG based on loop system fabricated from mode-locked ring laser, multi-project wafer run in an active and passive integrated process using multimode interference (MMI), semiconductor optical amplifier (SOA), electro-optic phase modulator, SA and passive waveguide, the best results of this work were 44 lines with flatness 1.8 dBm variation with maximum output power about -18 dBm. Shen *et al.* [16] designed OFCG span over 2 THz contain 200 optical comb line stronger than -20 dBm using fiber loop, optical phase modulator and erbium doped fiber amplifiers (EDFA).

For cascade technique, it adopted in [1]-[5], [7], [17]. Qu *et al.* [1] proposed a novel scheme to generate flatter and stable OFC based on chirping of two stages MZM, the first stage used dual-drive MZM with high chirp factor and for increasing the comb lines used integrated MZM in the second stage. The chirp factor is changed (α=5,7 and 9), the number of comb line was in the range between 15 to 21 with output power is about -20 dBm. Hmood *et al.* [2] designed a stable and flat OFCG based on MZMs with high chirping factor by two different methods, in the first one the electrical RF signal modulated the optical signal using a single MZM while the second used two cascades MZMs and time delay, the number of achieved comb lines was 13 with power fluctuation less than 1dB and power strength about -10 dBm. Zhang *et al.* [3] proposed a FCG based on two stages of polarization modulators (PolMs) and MZM. The first stage contains PolM and MZM produced 11 comb line with good flatness followed by the second stage which contains another PolM this will increase the comb lines by a factor of up to 5. The system is cost-effective. The frequency spacing between comb line was 5 GHz while the amplitude of RF signal is changed between three value, the maximum number of comb lines was 55 lines with fluctuation power 5.24 dBm and output power about -20 dBm. Ferreira and Rocha [4] presented a theoretical study with three techniques for implementing comb generator based on cascade model of modulator, RFS and discrete mode laser, stimulated the proposed design by optiSystem and compered between them in the term of bit error rate (BER). Ullah *et al.* [5] generating 60 comb lines with good power fluctuation about 0.7 dBm over 0.5 THz bandwidth based on a cascade module of pulsed laser diode, phase modulator and two MZMs. All modulators are driven by the same RF signal. This system was designed for implementing wavelength division multiplex passive optical network (WDM-PON) to support the 1.2 THz transmission data rate. Shen *et al.* [7] proposed a novel system of microwave frequency generator with Alta-flat broadband based. The system was easy to adjust and simple. The proposed scheme based on optical frequency comb (OFC) with multiple-quantum-well electro-absorption modulator (MQW-EAM) and contain top level domain (TLD) with EDFA. The spacing between lines can be adjusted by changing RF signal frequency from 5 to 20 GHz, the results show 15 comb lines with maximum output power is -30 dBm over 300 GHz effective bandwidth and 0.02 dBm power fluctuation. Ullah *et al.* [17] proposed a cascade module of three modulators, one amplitude modulation (AM) and two

MZMs with a laser diode to achieve a novel and effective frequency comb generator (FCG), RF signal of 30 GHz used to drive the three modulators and it is the spacing between the comb lines, number of flat comb lines generated was 61 with 40 dB TNR.

3. BASIC PRINCIPLE

OFCG as mention before using to generating a set of optical lines over a large bandwidth from the same laser source that will reduce the optical sources in the optical line terminal (OLT) and increase the transmission data rate of the system due to the multi carriers [17], [22], [23]. The proposed system was generating a set of optical comb lines for visible light communication (400-800 THz) and dense wavelength division multiplexing (DWDM) applications. The proposed as shown in Figure 1.

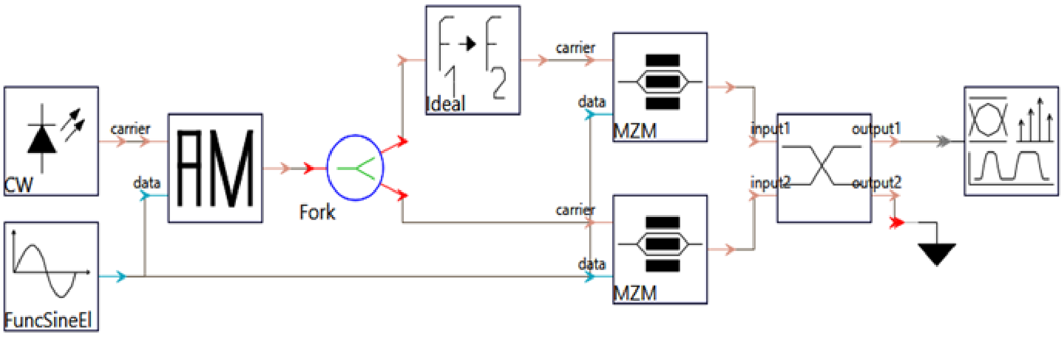


Figure 1. The proposing scheme of OFCG

The CW laser source was emitted at frequency 500 THz, the light of the laser source with frequency f_0 has an amplitude A_0 and phase φ_0. The probability density function is used to moduled the laser phase noise as:

$$f(\Delta\varphi) = \frac{1}{2\pi\sqrt{\Delta f dt}} \cdot e^{-\Delta\varphi^2/_{4\pi\Delta f dt}}$$

where $\Delta\varphi$ is the phase difference between two consecutive time instances and Δf is the line width of laser diode, between two successive time instance a summed a Gaussian random variable with zero mean and variance about $2\pi\Delta f$. A sequence of harmonic tones with $f_0 + nf$ components will be on the output of the amplitude modulator, where f is the RF signal frequency while $n = [0, 1, 2, \ldots]$ is the number of the harmonics. The output field of AM is given by [17], [24]:

$$E_k = |E_0| \sum_{n=\infty}^{-\infty} E_{n,k} \cos\left[2\pi(f_0 + nf)t + \theta_{n,k}\right.$$

$E_{n,k}$ and $\theta_{n,k}$ are the amplitudes and phases of component respectively [17]. The output of the amplitude modulator was driven into two branches one will be applied to the MZM2 and the other one will be shifted by $f_0 + n_{max}f$ and applied to MZM1. The modulators are driven by RF signal, the spacing of the generator comb lines can be tunable by RF signal frequency. All the modulators are driven by the same RF signal. The MZM have an output optical power depends on the $\Delta\emptyset$ of the two brunches [19], [25]:

$$P_{out}(t) = P_{in}(t) \cdot d(t) = P_{in}(t)\, cos^2[\Delta\emptyset(t)]$$

with

$$\Delta\emptyset(t) = \frac{\Delta\emptyset_1(t) - \Delta\emptyset_2(t)}{2}$$

$d(t)$ is the power transfer function while phase change in each brunch is $\Delta\emptyset_1(t)$ and $\Delta\emptyset_2(t)$ which is caused by applied signal.

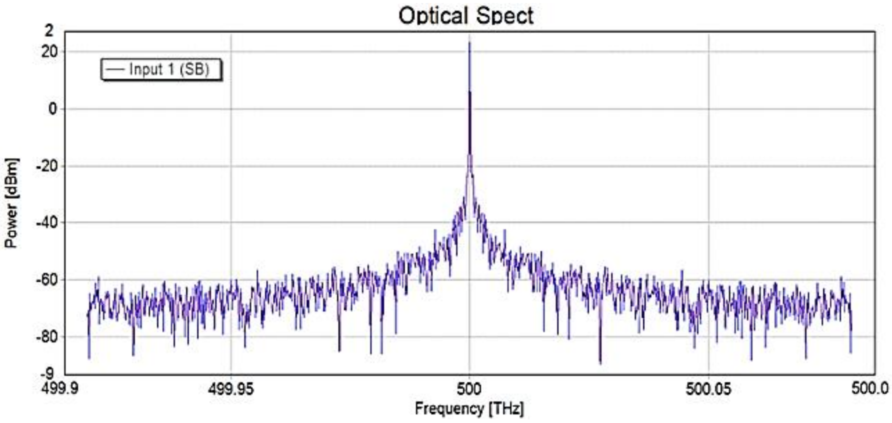
4. RESEARCH METHOD

The proposed system for generating optical comb lines for visible light communication and DWDM application as shown in Figure 1, the CW laser diode was used as an optical source emitted at 500 THz. The light of the laser has a spectrum with a single carrier frequency centered at 500 THz and many weak sidebands, applied to AM modulator to produce multi harmonics at the two sides of the center frequency. These harmonics are gradually decreased on both sides, the output of AM was separated into two branches by Fork, one of these directly passed through the MZM_2 and the other one shifted by phase shifter then passed through the MZM_1, frequency offset of the phase shift is equal to the AM bandwidth this process takes advantageous in double the overall system bandwidth. The output harmonics after $MZM_{1,2}$ was stronger and flatter, then combined using un optical coupler to produce the final signal of OFCG.

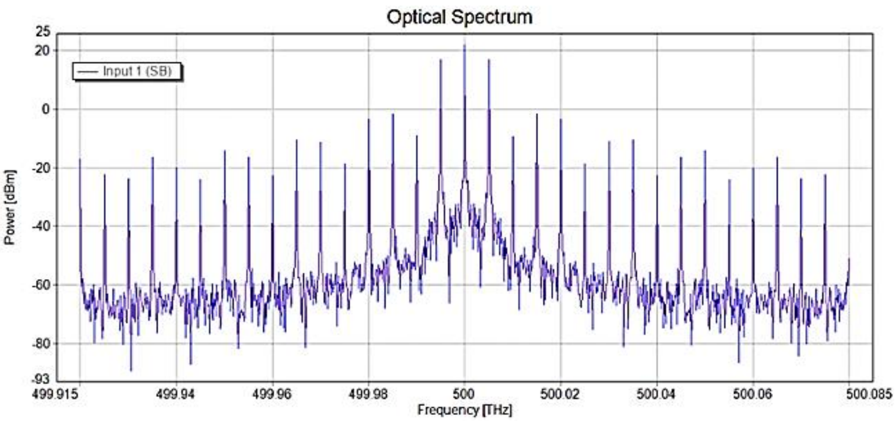
All the modulators were driven from the same FR signal. RF signal frequency is controlling on the duration of comb lined so the spacing between generating optical lines was tunable by RF frequency by increasing the frequency the spacing between optical comb lines will increase. The alpha factor of the MZMs is varied over 3, 5, 7 to experience the best result of OFCG. The proposing OFCG has a very good result in term of flatness and output power compared to the many previous works. We obtained 64 comb lines over 340 GHz bandwidth; the output power reaches to 8 dBm.

5. RESULTS AND DISCUSSION

The proposed system was stimulated using VPIphotonic design suite 9.8, all the parameters were used for designing the system was explained in Table 1. Figures 2(a), (b) show the output of the CW laser diode and the AM modulator. AM produces multiple harmonics of the input signal on the two sides of CW center frequency of optical spectrum after passed this signal through the two parallel MZMs these harmonics will be stronger and flatter, the value of alpha-factor affects the flatness of these harmonics as demonstrated in Figures 3(a), (b), (c).



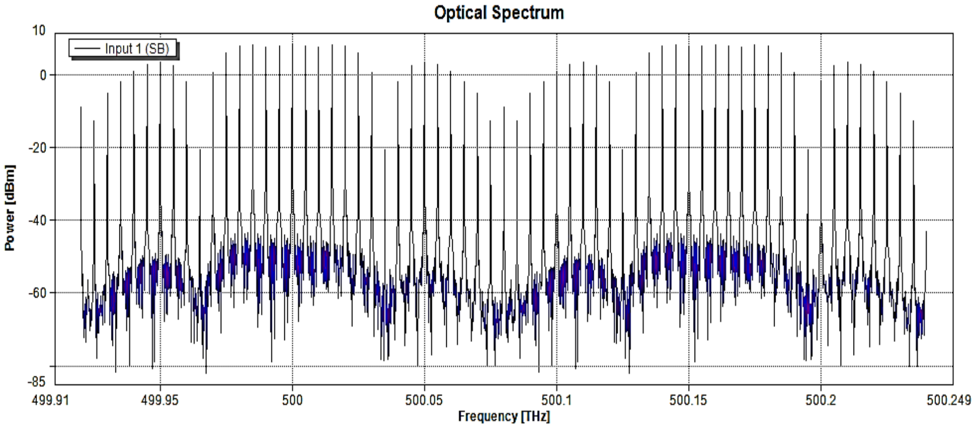
(a)



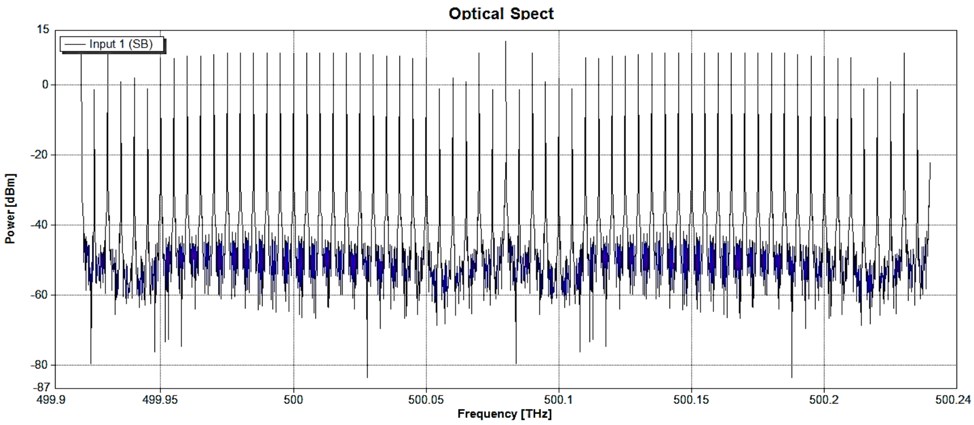
(b)

Figure 2. Output optical spectrum of (a) CW laser, (b) AM modulator

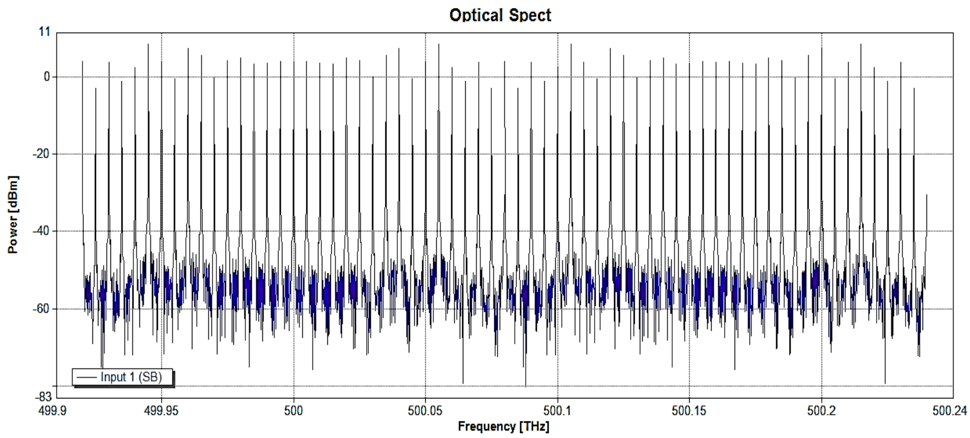
As the results, we obtained 64 comb lines for VLC frequencies with spacing is 5 GHz this spacing easy tunable by FR signal frequency, the bandwidth of the proposed system is 340 GHz, the Figure 3 shows the output of the proposing OFCG with three different values of alpha-factor, the best results belong to the value 5 of an Alpha factor due to the high flatness. Table 2 explains the measured parameter of stimulated OFCG, the best results related to α=5 with excellent flatness with strong output power. As shown in Figure 3(b), the overall comb lines results is very good compared with mentioned previous work in section 2, there are 42 smooth and strong comb lines with power fluctuation 0.5 dBm, and the other comb line ranges between -1.77 dBm and -2.14 dBm.



(a)



(b)



(c)

Figure 3. The generation of OFC lines with: (a) α=3, (b) α=5, (c) α=7

Table 1. The parameters of proposed OFCG

The Device	Parameter	Value
CW Laser	Emission frequency	500 THz
	Average power	0.2 W
	Linewidth	100 KHz
	Azimuth	45 deg
AM Modulator	Modulation index	1
Phase Shirt	Frequency offset	160 GHz
RF Signal	Frequency	5 GHz
	Amplitude	2 a.u.
	Bias	1 a.u.
MZMs	Extinction ratio	35 dB
	Alpha factor	3, 5, 7

Table 2. The stimulated results

Alpha Factor	Maximum Output Power (dBm)	Minimum Output Power (dBm)
α=3	8.83	-20.41
α=5	8.09	-2.14
α=7	10.10	-2.39

6. CONCLUSION

We designed an efficient scheme of optical frequency comb generator (OFCG) based on AM modulator, phase shift and two parallel MZMs for generating a set of carrier frequencies from a single laser source to reduce the optical sources at the transmission side with maximizing the transmission data rate, the system generated comb lines over VLC frequencies and it can be advantageous in the VLC and DWDM applications, and characterized by its simplicity and tunability. The proposed scheme was designed and stimulated by VPIphotonic design suite 9.8. OFCG generates 64 flat comb lines with output power stronger than -2 dBm over 340 GHz bandwidth, from these lines there is 42 lines with an output power of about 8 dBm and fluctuation less than 0.5 dBm. The spacing between comb line was easily tunable by the RF frequency signal This paper also presented the effect of varying chirping factor of MZMs with three different values (α=3, 5, 7), the best results related to α=5.

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