Simulation study on optoelectronic oscillator based simultaneous V – band and terahertz signal generation

ANU SAM*, M. GANESH MADHAN
Department of Electronics Engineering, Madras Institute of Technology, Anna University, Chennai-600044, India

Wideband optical frequency comb(OFC) generation based on 2 stage electroabsorption modulator(EAM)with tunable frequency spacing is proposed.A tunable opto electronic oscillator(OEO) forms the basis of this scheme,where V band millimeter waves(57GHz-64GHz) are generated in the first stage.Optical bandwidth of 4.3THz is derived by combining the first stage OFC and a laser output,which is then modulated by an EAM.The frequency distinction between the two lasers is chosen, so that 110 comb lines within 6dB power variations are generated, with a frequency spacing of 44GHz.This scheme provides a simple structure for generating comb lines with an Optical signal to noise ratio(OSNR) of 35dB.The highlight of this work is the simultaneous generation of V band millimeter waves(57GHz-64GHz) and terahertz waves based on OEO without an electrical filter.This scheme can find application in 5G and future communication systems,as an optoelectronic tunable millimeter (mm)wave source.

(Received April 22, 2024; accepted December 2, 2024)

Keywords: Optical frequency comb (OFC), Electroabsorption modulator(EAM), Wavelength selective switch (WSS), V band, Millimetre waves (mm waves), and Terahertz generation

1. Introduction

The demand for huge bandwidth remunerates attention in sub terahertz and terahertz wave communication [1]. Therefore, generation of sub terahertz and terahertz waves has gained interest in recent days. Optical frequency comb (OFC) based carrier generators are observed as a low cost, flexible and spectrally efficient method for terahertz generation [2]. Optical frequency comb is a sequence of uniformly separated distinct frequency components. It provides excellent phase noise behaviour and thereby fits for various applications like spectroscopy, laser ranging and optical communications [3]. Different techniques have been reported for the generation of optical frequency comb lines. Jian Wang et al. [4] demonstrated the generation of 7 OFC lines using dual parallel mach zehnder modulator (DPMZM) and achieved a flatness of 1. 26dB. In this case, less number of comb lines are generated, which is a limitation of this scheme. In order to increase the number of comb lines, multiple lasers are modulated by single mach zehnder modulator [5] and cascaded modulators [6]. To eliminate the need for an external RF source, Jian Dai et al. [7] proposed an optoelectronic oscillator for the generation of 11 comb lines with less than 1 dB flatness using cascaded configuration of MZM and a phase modulator. The above mentioned OFCG methods use electrical filter in the OEO, which causes a bottleneck of tuning over narrow pass band. An electrical filter free SBS based OEO is designed and attained 9 comb lines with 3dB flatness [8].

An electro-absorption modulator based parametric optical frequency comb generator is designed and achieved 10 OFC lines with 5dB amplitude variations [9]. A self-starting OFC generation based on VCSEL is illustrated [10]. The self-starting OFCG does not require any microwave input signal. An uneven OFC is generated using a polarization modulator and flatness is further improved by employing a first order butter worth filter [11]. Broad and flat OFC can be generated by utilizing the fibre nonlinearity, four waves mixing. OFCG (Optical frequency comb generation) is initiated using 50GHz spaced two lasers and single MZM [12]. Similarly, OFC is generated by utilizing SBS and four wave mixing. The high pump power contribution at the recycling loop is reduced by power equalization [13]. Tunable OFC generation using a phase modulator and electro-absorption modulator based on self oscillating OEO with a bandwidth of 1.28THz is demonstrated [14]. Pan Jiang [15] proposed an electro-absorption modulator based OFCG using a multiplication coupler. This device consists of an electrical power splitter and an arithmetic unit to generate multiple radio frequencies, which drives the EAM. Furthermore, Jing liang Liu [16] reported a novel method to produce 30 OFC lines with flatness less than 6dB by an OEO using recirculation frequency shifter (RFS) loop. A novel scheme of OFCG is proposed using one dual parallel mach zehnder modulator (DPMZM) driven by superimposed harmonics. 9 comb lines with 0.26dB flatness are achieved [17]. Broadband OFC's can be generated using nano lasers with gain switching [18]. Multi frequency millimetre waves are generated using OFC based on gain switched lasers and 5G NR 64QAM data transmission with less phase noise is reported [19]. Recently, a flat OFC is generated by employing a cascaded configuration of 2 frequency modulators and MZM. The number of OFC lines was enhanced to 70, within an amplitude variation of 2dB [20]. With the aim to enhance the bandwidth to 2.74THz, 2 stage OFC's generated by 2 lasers and MZM's, were heterodyned and 137 comb lines with (0-6dB) flatness are produced [21]. But this technique uses an external RF source to drive the EAM, which creates noise.

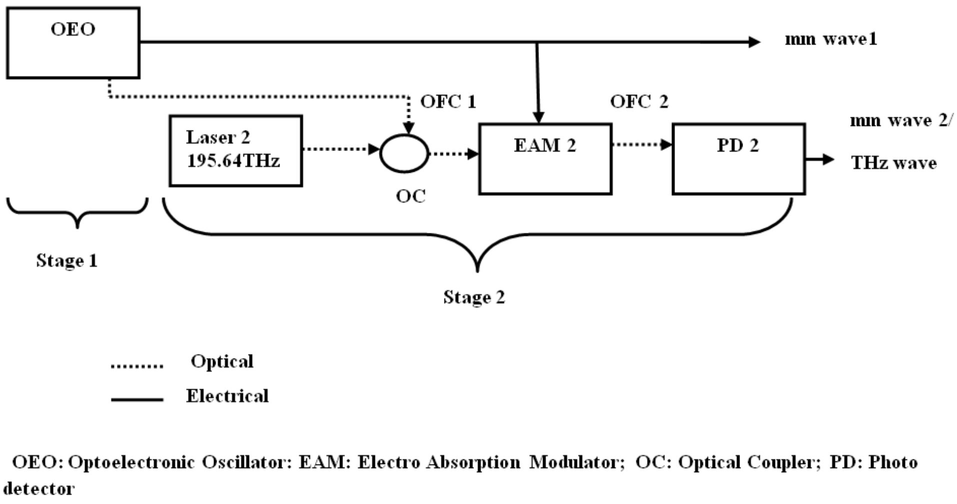


Fig. 1. Schematic representation of the proposed OFCG using OEO

From the literature, it is observed that most of the techniques utilize RF source, electrical filter and fibre nonlinearities for the generation of OFC. Hence, there is a need for optical comb generation with large bandwidth and less complexity, for applications requiring millimetre (mm) and terahertz wave generation.

In this paper, a novel OFC generator based on EAM and Opto electronic oscillator (OEO) is proposed. The first stage OFC is generated by modulating the laser carrier using EAM 1and it is coupled with a second laser source (laser2), whose output is further modulated by an EAM. The modulating signal is obtained by an optoelectronic oscillator arrangement involving EAM 1, wavelength selective switch (WSS), amplifiers and photodiode. Further, this arrangement does not require an electrical filter. Moreover, electro optic modulator (EOM) is replaced by EAM and the need for an external RF source is eliminated, results in higher bandwidth compared to [21]. As compared to Ref. [14], the proposed work used an OEO without an electrical filter which eliminates the bottleneck caused by the electrical filter. The influence of laser power, frequency spacing and amplifier gain on amplitude variations of comb lines are also examined using optic system software, for identifying the optimum parameters. Terahertz wave generation by photo detecting the EAM2 output (stage2), along with V band millimetre wave from OEO in stage 1 is verified in this technique. As the lower millimetre wave bands up to 30GHz is highly overcrowded, the 60 GHz (V-band from 57 to 64 GHz) unlicensed industrial-scientific-medical (ISM) band is expanding research attention in nowadays. The highlights of this work are endorsed as follows:

i) Tunable self oscillating OFC is generated based on 2 stage electro-absorption modulators and bandwidth is enhanced up to 4.3THz.

ii) Need for conventional method of RF generation is avoided and substituted by a simple OEO without an electrical filter, which is achieved by detecting the first stage EAM output.

iii) Simultaneous generation of V band (57GHz-64GHz) millimetre waves and terahertz waves are performed.

iv) This scheme is equipped with a simple structure to enhance the bandwidth and generate comb lines having amplitude variations within 6dB.

2. Principle of operation

Fig. 1 depicts the schematic of the proposed optical frequency comb generation utilizing an efficient 2 stage EAM modulation. A wideband optical frequency comb (OFC) spectrum is obtained by combining the OFC’s generated using 2 lasers [21]. The 2 laser frequencies are selected in such a way to provide an effective frequency distinction of 2.56THz. This architecture deploys electro-absorption modulators (EAM) instead of conventional electro optic modulators, due to its low losses and requirement of less driving voltage. It is compact and can be integrated with lasers on a single chip. It recommends high speed modulation with improved bandwidth and reduced chirp. It also generates significant number of carriers which are used for deriving the EAM drive signal and creates larger frequency distinction. In the first stage, EAM1 output produces the first optical frequency comb (OFC1). The OEO signal is generated by selecting the suitable optical sidebands within the first stage, using a Wavelength Selective Switch (WSS) and it is converted to mm wave 1 at the photo detector, thereby avoiding the need for external RF oscillator and electrical band pass filter, as shown in Fig 2. The sustained oscillations of the OEO depend on the gain and physical length delay of the feedback loop [22].

The amplitude and the frequency of the OEO signal can be calculated as

$$V_{\mathrm{mod}} = V_{in} G \tag{1}$$

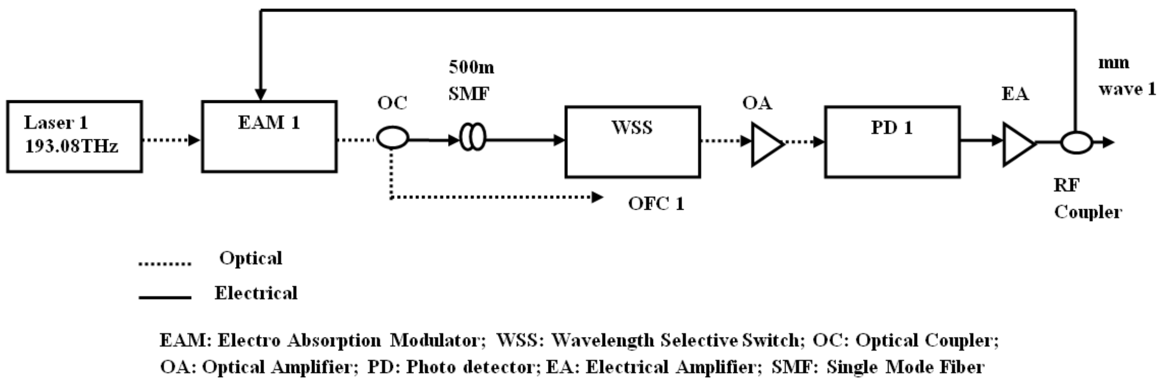


Fig. 2. Schematic diagram of OEO (stage 1)

$$f_{osc} = k/\tau \quad \text{If } G > 0 \tag{2}$$

G is the gain and τ is the delay of feedback loop.

The resultant OFC from the second stage generates 110 carriers within 6dB amplitude variations and achieves a bandwidth of 4. 3THz. Moreover, the first stage OEO produces millimetre wave1 in the V band spectrum (57GHz-64GHz). As the driving signal frequency (frequency spacing) increases to millimetre wave range, the amplitude variations of final OFC reduce to a value less than 5dB. Mathematically, OFC generation is interpreted as follows:

The optical electrical field of laser 1 is given by

$$E_{laser1}(t) = E_1 e^{j\omega_1 t} \tag{3}$$

The OEO signal used to drive the EAM is expressed as a microwave signal [14] and it is given by

$$V_{OEO}(t) = V_{mod} \sin w_c t \tag{4}$$

Where is w_c the OEO angular frequency, V_{mod} is the amplitude of the modulating signal.

The optical output of first stage EAM is given as

$$E_{EAM1}(t) = E_1 e^{j\omega_1 t}.[(V_{mod}(t))^{\frac{1}{2}} e^{j\alpha_1 f_c(mod(t))}] \tag{5}$$

The first stage EAM output is coupled with second laser of electric field $E_{laser2} = E_2 e^{j\omega_2 t}$ using an optical coupler. The output of the optical coupler is represented as

$$E_{coupler} = E_1 e^{j\omega_1 t}.[(V_{mod}(t))^{\frac{1}{2}} e^{j\alpha_1 f_c(mod(t))}] + E_2 e^{j\omega_2 t} \tag{6}$$

The coupled optical field is modulated by the second stage EAM. The modulated output of EAM2 is given as

$$E_{EAM2} = \{E_1 e^{j\omega_1 t}.[(V_{mod}(t))^{\frac{1}{2}}.e^{j\alpha_1 f_c(mod(t))}].[(V_{mod}(t))^{\frac{1}{2}} e^{j\alpha_2 f_c(mod(t))}]\} + E_2 e^{j\omega_2 t}[(V_{mod}(t))^{\frac{1}{2}} e^{j\alpha_2 f_c(mod(t))}] \tag{7}$$

$$E_{EAM2} = E_1 e^{j\omega_1 t}..\{(1-\gamma)^{\frac{1}{2}}[(\gamma.\sum_{k=\infty}^{\infty} j^k J_k(\gamma) e^{jkwt})]^{\frac{1}{2}}.e^{j\alpha_1 (mod(t))}\} + E_2 e^{j\omega_2 t}.\{(1-\gamma)^{\frac{1}{2}} + [(\gamma.\sum_{k=\infty}^{\infty} j^k J_k(\gamma) e^{jkwt})]^{\frac{1}{2}}.e^{j\alpha_2 f_c(mod(t))}\} \tag{8}$$

The equation (8) is obtained by applying Jacobi-Anger identity and elaborated by Bessel functions

Where α and ɣ are the chirp factor and modulation index of all EAM's respectively. $f_c(mod(t))$ can be approximated using Taylor series at DC bias, V_{bias} as [20]

$$f_c(mod(t)) = \sum_{\delta=0}^{\infty} (\frac{1}{\delta!}) f_c^{\delta} V_{bias}.[V \sin(2\Pi f_c t)^{\delta}] \tag{9}$$

where $f_c^{\delta} V_{bias}$ is the δ^{th} order derivative of f (mod (t))

Equation (8) predicts the generation of large number of optical comb lines, without involving any external RF source and also provides enhanced bandwidth compared to ref [21]. The intensity and amplitude variations of comb lines are controlled by drive voltage chirp factor and modulation index of EAM's. The tunable frequency spacing also influences the flatness of comb lines.

3. Simulation results and discussion

The proposed two stage optical frequency comb generator (OFCG) for enhanced bandwidth shown in Fig. 1 is simulated using OptiSystem 16 platform. In this scheme, the OFC generation is done in 2 stages. In the first stage, a laser source of central frequency 193.08THz generates a power of 15dBm, with a line width of 1MHz. Electro-absorption modulator with reverse bias voltage of -1.5V modulates the laser carrier.

The impact of laser power, frequency spacing and RF amplifier gain on amplitude variations and number of OFC lines are examined as follows, to identify the optimum parameters.

3.1. Effect of laser power

In the OEO stage, the electrical feedback signal from the photodiode depends on the optical signal falling on it. This factor is controlled by the laser power and modulation depth.

Therefore the launching power of the first laser has a remarkable role in determining the driving signal of EAM. To analyse the effect of laser power, its value is varied from 3dBm to 20dBm and the amplitude of OFC lines are studied. As the laser power increases, the OFC attains minimum amplitude variations.

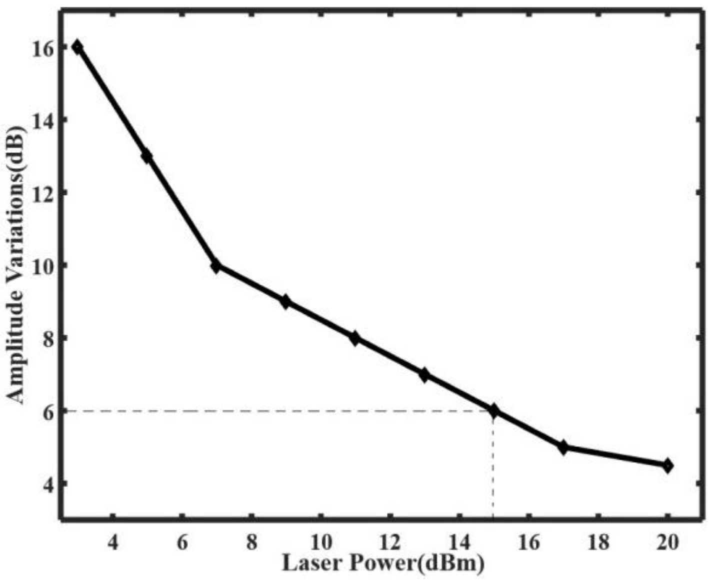


Fig.3. Impact of laser power on amplitude variations of OFC lines

It is observed that, stable comb lines having amplitude variations within 6dB can be generated with a frequency spacing of 44GHz, when the laser power exceeds 15dBm,as shown in the Fig. 3. However, practical limitations of the photodetector restricts the optical power to 18dBm. Hence a maximum laser power of 15dBm is fixed for the OEO.

3.2. Effect of frequency spacing

The frequency of the OEO is determined by WSS and the photo detector.

Wavelength selective switch is basically a WDM multiplexer/demultiplexer. It can add/drop single or group of wavelengths [23]. In our study, two wavelengths are selected for the mm wave generation in the OEO. The proposed technique can render a broad bandwidth of 4. 3THz.The first stage OFC provides a bandwidth of 1.802THz only, with 42 comb lines having amplitude variations within 6dB. By adjusting the WSS frequencies, the frequency spacing is changed from 10GHz to 60GHz and the resulting OFC is examined.

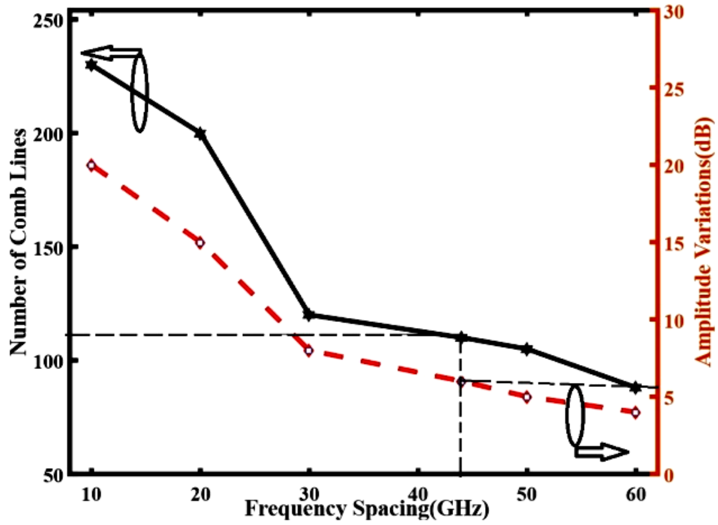


Fig.4. Effect of frequency spacing on amplitude variations and number of OFC lines (color online)

It can be observed from the Fig. 4, that, as the frequency of OEO rises, large number of carriers is generated with reduced amplitude variations. It is inferred that, the optimum number of comb lines having amplitude variations in the range of 5-6dB can be generated within the frequency spacing of 40GHz to 50GHz. Moreover, 88 comb lines are generated with amplitude variations (<5dB), when the modulating signal frequency turns to 60GHz. Similarly for a minimum frequency spacing of 10GHz, large number of carriers are generated, but the OFC may be unstable as the comb lines have high amplitude variations.

3.3. Effect of RF amplifier gain

The reverse bias Voltage applied to EAM is expressed as

$$V_{bias} = V_{DCbias} + V_{RF} \sin w_c t \qquad (10)$$

where $V_{DC\ bias}$ is the reverse DC bias voltage and V_{RF} is the peak voltage of the modulating signal. The maximum amplitude variations between the comb lines is referred as flatness of the OFC[16].

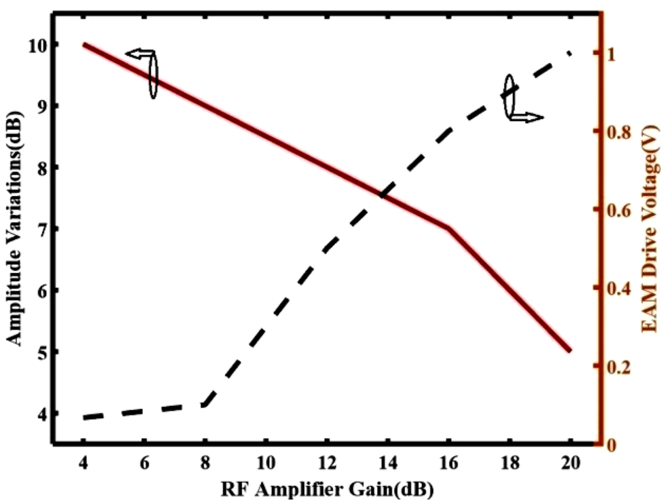


Fig.5. Effect of RF amplifier gain on amplitude variations of OFC lines and EAM drive voltage (color online)

For high negative values of chirp factor, EAM should be operated at large reverse bias. Therefore the EAM driving voltage is determined as 1V for attaining the required reverse bias. It can be observed from the Fig. 5 that as the gain increases, the modulating voltage used to drive the EAM also increases. When the chirp factor becomes more negative, absorption rate is maximum and extinction ratio is reduced at the cost of flatness.

For low amplifier gain of 5-10dB, the chirp factor requirement is not fulfilled and also the amplitude variations are maximum. The minimum amplitude variations is realised by fixing the amplifier gain as 20dB.

3.4. Effect of optical amplifier gain

OSNR is a measure of signal power degradations caused by Amplified Spontaneous Emission(ASE) noise accumulated by optical amplifiers.The gain of optical amplifier(OA1) is varied from 5 to 30dB, and the effect of noise power is observed in Fig.6. It is found that, OSNR drastically reduces at 30dB gain for each of the frequency spacing,as the noise power also get amplified along with signal power. This is in accordance with theory, OSNR also tends to increase with frequency spacing and then reduces for a higher frequency spacing.

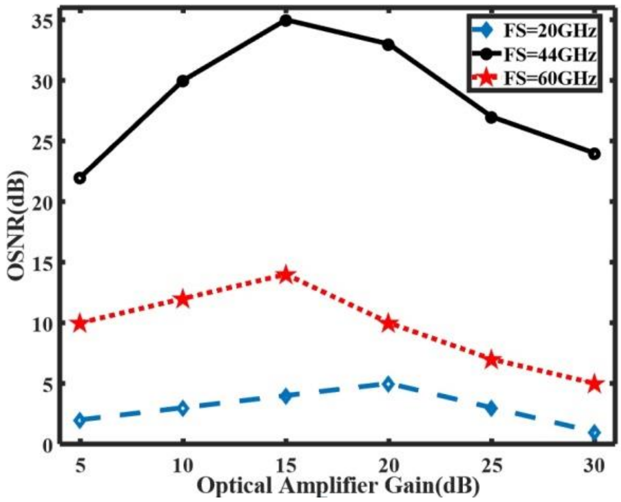
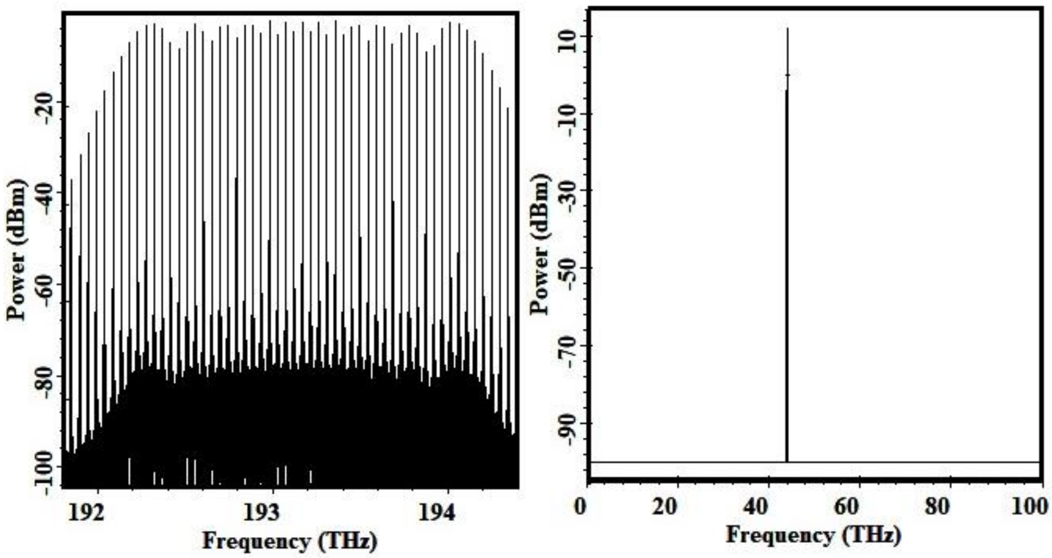


Fig. 6. Variation of OSNR with amplifier gain for different frequency spacing (color online)

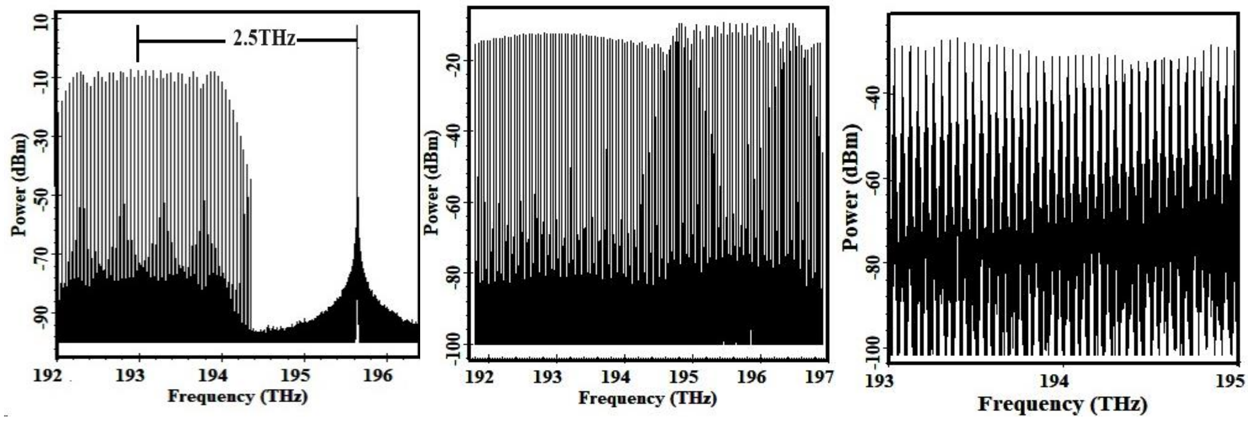
This is due to the fact that tuning a higher frequency spacing of 60GHz, the optical sidebands needed to heterodyne at the PD, becomes weak and therefore larger gain is demanded to meet the chirp factor requirement. The demand for higher gain degrades OSNR. The chirp factor has a positive impact on the generation of number of comb lines. It can be noticed that the optimum gain to guarantee a tradeoff between OSNR and number of comb lines is found to be in the range of 15-20dB. For a frequency spacing of 10GHz, the amplitude variations of comb lines is high and hence the signal power is reduced. A favourable OSNR range of 30-35dB is obtained for an amplifier gain of 15-20dB. When the frequency spacing is tuned to 44GHz, at a fixed amplifier gain of 15dB. This condition predicts 110 comb lines within 6dB amplitude variations. Based on the above parameteric study, the optimum value of laser power,frequency spacing, RF amplifier gain and optical amplifier gain are fixed as 15dBm, 44GHz, 20dB, 15dB respectively.



(a) *(b)*

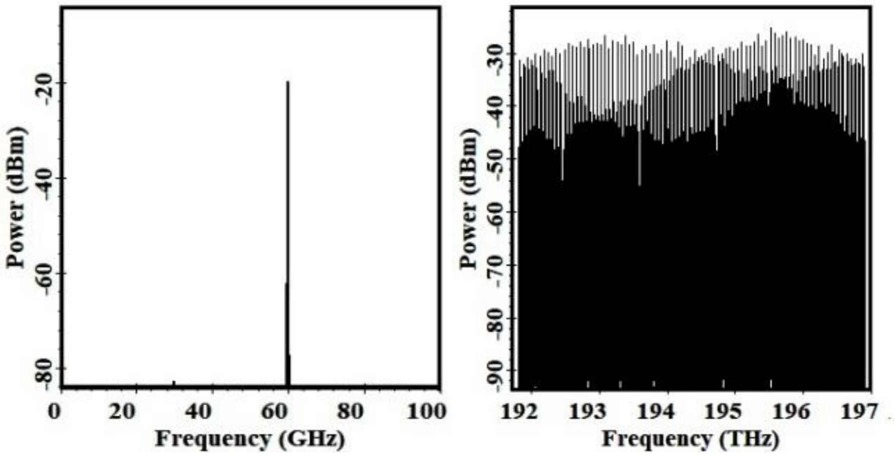
Fig. 7. (a) Optical spectrum of generated OFC at the first EAM (b) Electrical spectrum of OEO signal at stage 1, 44GHz

Fig. 7 (a) shows 59 carriers having amplitude variations within 16dB produced by EAM1. This modulated output provides the required OEO signal to drive the EAM by selecting desired optical sidebands using WSS, as shown in Fig. 7 (b). The OEO consists of wavelength selective switch (WSS), Photo detector and electrical amplifier, which can generate signal in the V band spectrum, for an RF amplifier gain of 20dB. The first stage modulated optical output gets coupled with another laser source (laser 2) by an optical coupler with a coupling coefficient of 0.5 and the combined spectrum is shown in Fig.8 (a). The frequency of the second laser is precisely fixed as 195.64THz with a launching power of 10dBm, so that the weak sidebands of first stage OFC are effectively combined.



(a) *(b)* *(c)*

Fig.8. Optical spectrum of (a) coupled output, (b) combined OFC at the second stage, (c) expanded version of OFC



(a) *(b)*

Fig 9. (a) Electrical spectrum of 60GHz OEO signal (b) Final OFC at the second stage

The first stage modulated output provides a larger frequency distinction of 2.56THz between the 2 lasers. The coupled output is further modulated by two EAM's and provides 110 comb lines having amplitude variations within 6dB with a frequency spacing of 44GHz, as observed in Fig. 8 (b). The expanded version of combined OFC is depicted in Fig. 8(c). The suggested scheme is not simply focused on combining 2 OFC's as in ref [5]. It can be observed that large number of comb lines is generated due to the fact that in the second stage, EAM modulates both OFC1and laser 2 carrier. This scheme achieves a high bandwidth of 4.3THz, which takes over more than half of the optical C band by strengthening the weak sidebands of OFC1. The proposed scheme offers high OSNR of around 35dB, with less noise power of -57dBm. Compared to electro optic modulator, EAM modulates both intensity and phase of the carrier and provides enormous number of carriers with narrow width and less phase noise, which fits for terahertz generation.

Fig. 9 (a) shows the electrical spectrum of 60GHz millimetre wave generated by OEO at the first stage. This 60GHz modulating signal produces 88 carriers with flatness of 5dB at the output of EAM 2 and is shown in Fig. 9(b). Millimetre waves are generated by heterodyning the desired optical sidebands at the photo detector(PD1). One wavelength is fixed in the Wavelength Selective Switch(WSS) and the other one is varied in the range of 191.8THz -193THz. In this arrangement, terahertz waves can be generated at uni travelling carrier photo detector(PD2) which is an InP/ InGaAs UTC with responsivity of 0.51A/W [24]. By heterodyning the comb lines from the last stage EAM, produces signals in the range of 0-1THz as shown in Fig.10.

This is in addition to the V band signal generation in OEO at the stage 1.

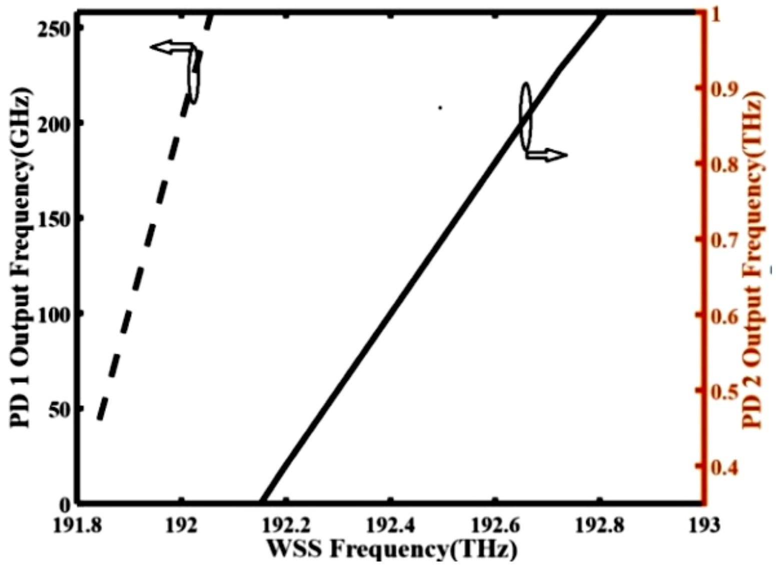


Fig.10. Simultaneous generation of mm waves and terahertz waves (color online)

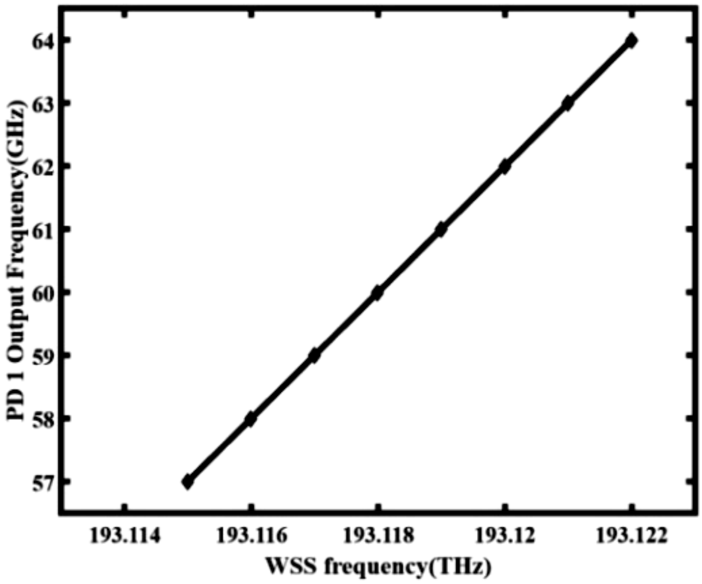


Fig.11. Generation of V-band mm waves

Table1. Comparison of proposed and existing works

Cited Work	Components used	Type of modulating signal	Bandwidth
[14]	1laser,phase modulator,EAM	OEO with electrical filter	1.28THz
[16]	1 laser,4 dual drive MZM	Recirculating loop	1.4THz
[20]	1laser,2 frequency modulator, 1 MZM	3 RF sources	300GHz
[21]	2 lasers,2 MZM	RF source	2.74THz
This work	2 lasers,2 EAM	OEO without electrical filter	4.3THz

It can be observed from the Fig.11. that V band mm waves (57GHz-64GHz), finding application in 5G and 6G wireless communication, can be produced by selecting the desired comb lines of first stage OFC spectrum. Hence one of the stable comb line frequencies, 193.058THz has to be fixed. This V band mm wave can serve as the OEO signal to all EAM's. The above-mentioned method of generating mm waves looks advantageous, as it does not need any separate RF source, frequency multiplication (frequency tupling) techniques.

Comparison with similar schemes illustrates the merits of the proposed work. Refs. [20] and [21] employed external RF source for the generation of OFC. But proposed work utilized OEO without an electrical filter, attained a higher bandwidth compared to [14].

4. Conclusion

A new scheme to enhance the bandwidth of OFC by using 2 laser sources and 2 stage EAM modulation is proposed in this work. It can guarantee superior performance in comparison with conventional electro optic modulators. The impact of frequency spacing, laser power and amplifier gain on number of comb lines and amplitude variations are analysed to provide optimum parameters for effective OFC generation. The proposed technique can produce 110 comb lines within 6dB amplitude variations and attained an effective bandwidth of approximately 4.3THz, without the requirement of a RF source. This bandwidth covers more than half of the optical C-band and makes it suitable for mm wave and terahertz wave generation. It has the merits of high bandwidth, simple and electrical filter free structure. It also offers a high OSNR of 35dB for a frequency spacing of 44GHz. In future,the attributes of EAM can be further investigated to enhance the bandwidth of OFC without using an additional laser. The degradation of OSNR for higher frequency spacing also has to be focussed by implementing new techniques.

Acknowledgements

The authors acknowledge Anna University, Chennai for granting financial support to carry out the research work under Anna Centenary Research Fellowship(ACRF) scheme. One of the authors, Anu Sam is grateful to Anna University, Chennai for the award of Anna Centenary ResearchFellowship[RefNo:CFR/ACRF/21254391260/AR1].

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*Corresponding author: anusam@mitindia.edu