Terahertz and millimeter wave generation scheme based on stimulated Brillouin scattering driven optical frequency comb

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In this paper, a tunable terahertz wave generation scheme based on Stimulated Brillouin Scattering (SBS) is proposed. This method does not need any pre assigned Radio Frequency signal to activate the modulators. The Brillouin shift frequency (11GHz) with a phase noise of -96dBc/Hz can be generated by utilizing SBS. It serves as the modulating signal for driving the Electro Absorption Modulator (EAM). The deployment of cascaded configuration of EAM compensates the limitation of fixed driving signal. This scheme offers a wideband optical frequency comb (OFC) spectrum of 117 optical carriers with an approximate bandwidth of 1.287THz, in which 41 comb lines have approximately 5dB flatness. Wavelength selective switch (WSS) chooses the desired optical comb lines, 192.858THz and 193.342THz to generate 0.484THz wave with a phase noise of -78dBc/Hz for 10 kHz frequency offset. By varying the selected comb lines, tunability of millimeter and terahertz waves can be achieved.

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1. Introduction

There is an incredible demand for high data rate and bandwidth for the expanding wireless communications. This scenario is encountered by integrating high-capacity fiber and wireless links operating at millimeter (mm) and terahertz (THz) waves. Terahertz and millimeter waves play an important role in achieving high data rate transmission with adequate bandwidth for 5G and future 6G wireless networks [1, 2]. The generation of spectrally pure mm and THz waves is a critical task. The conventional electronic schemes of mm wave generation are not economical and modulation bandwidth of electronic devices is limited. Therefore, synthesis of terahertz waves by photonic assisted methods has gained recent research interest [3]. Photonic schemes include heterodyning of two laser outputs, using Stimulated Brillouin Scattering (SBS) [4] and optical frequency comb generation [5]. Heterodyning of two lasers and frequency multiplication techniques induces phase noise which affects the system performance. The most reliable way to produce mm and terahertz waves is generating optical frequency comb (OFC). It is a sequence of evenly spaced discrete optical frequency carriers and extensively used in RF signal generation, signal processing, arbitrary waveform generation, optical communication [6]. This scheme is established with optical modulators driven by external RF signal to achieve flat comb lines [7]. Optical frequency comb generation based on external modulators require radio frequency oscillator to generate sidebands which decide the frequency spacing. However, it is enviable to relinquish RF oscillator, which drives the external modulator with an optoelectronic oscillator (OEO). Thus, OEO has gained interest in recent days due to its ability to generate stable and pure microwave from optical frequency comb lines [8]. Moreover, a tunable OEO based on stimulated Brillouin scattering with widest frequency spacing of 60GHz is demonstrated [9]. But this scheme requires a pump laser to activate SBS in single mode fiber. Generation of seven comb lines with flatness of 1.26dB using dual parallel Mach-Zehnder modulator is reported [10]. In order to enhance the number of comb lines and minimize the power variations, multiple laser sources can be employed [11], which in turn creates phase noise and therefore OFC can be produced with a single laser and cascaded configuration of modulators [12-15]. Few researchers have investigated the generation of THz waves using cascaded modulators with in phase and quadrature (I/Q) modulator [16]. OFC can be generated with tunable frequency spacing by an OEO based on recirculation frequency shifter loop [17]. Generation of parametric OFC using an electro absorption modulated laser cascaded with phase modulator is demonstrated [18]. However, self-oscillating OEO requires an electrical filter to tune the frequency spacing. This restricts the tuning of narrow pass band frequency. To mitigate this problem, tunable OFC can be generated by OEO with a Fabry Perot etalon [19]. Optical frequency comb can be effectively generated using stimulated Brillouin scattering based OEO, which also avoids the use of electrical filter [20, 21]. Recently a simple broadband OFC generation using an electro absorption modulator (EAM) driven by multi frequency signal, is reported. The driving RF signal is generated by employing a multiplication coupler [22]. Microwave and millimeter waves can be generated by frequency down conversion using short cavity fiber laser. This is achieved by utilizing two longitudinal laser modes [23].

In this work, a novel terahertz and millimeter wave generation scheme employing SBS based optical frequency comb is proposed. All the above-mentioned works in the literature, used additional circuitry, electrical filter, multiple RF signals to generate desired number of OFC lines at the outlay of stability, cost and complexity. Unlike the existing schemes, the proposed method uses a simple and economical structure without compromising the number of OFC lines and power variations. The highlight of proposed scheme is the generation of terahertz by SBS, utilizing single laser source and EAM for OFC generation. Frequency tunability on the generation of millimeter waves and terahertz waves are also implemented in this work.

The key focus of this work is mentioned as follows:

i) Generation of tera hertz and millimeter wave signals using stimulated Brillouin scattering (SBS) utilizing single laser source thereby terminating the demand for an additional laser and external RF oscillator.

ii) The limitation of fixed driving signal is compensated by the utilization of cascaded configuration of EAM's.

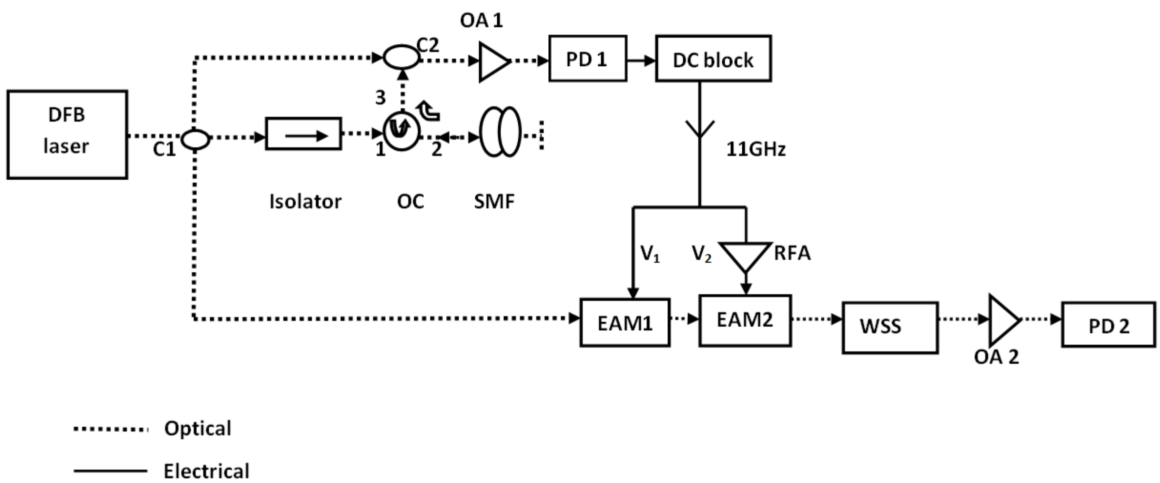
iii) This scheme offers cost effective and simple structure while enhancing the bandwidth of OFC spectrum using EAM.

iv) Frequency tunability of millimeter waves, sub terahertz and terahertz waves are also realized.

2. Principle of operation

Fig. 1 illustrates the proposed tunable terahertz wave generation by optical frequency comb (OFC) established on stimulated Brillouin scattering (SBS). Gao [24] demonstrated the stimulated Brillouin scattering based generation of RF signal (11GHz) using single laser source. This work utilized electro absorption modulators instead of standard electro optic modulators as the losses and drive voltage requirement are very low. A DFB laser generates optical signal, which acts both as signal and pump source, thereby reducing the phase noise due to an additional pump laser. The optical signal is delivered into a Single Mode Fiber (SMF). When the signal power reaches the SBS threshold (8dBm), backscattered stoke wave propagates in the opposite direction of signal transmission. As a result, a stoke wave (υ_c-υ_b) with a Brillouin frequency downshift (υ_b) of 11GHz, is made available at the port 3 of optical circulator [24].

At the PD 1, the beating of stoke wave (υ_c-υ_b) and the pump wave (υ_c) occur and 11GHz microwave signal is generated [25]. DC block suppresses all the dc components present along with 11GHz signal. RF amplifier magnifies the signal for driving the electro absorption modulator. This Brillouin shifted frequency eliminates the requirement of an external RF oscillator. The gain due to the stoke wave can be used to generate the 11GHz, which is stable [24, 26]. We have validated our simulation results with the existing experimental results mentioned in [24] [26] for the generation of 11GHz (frequency downshifted stokes wave) due to SBS effect. The phase noise generated due to external RF synthesizer is comparatively higher than generating RF signal by SBS at lower offset frequency [29].



OA: Optical amplifier; OC: Optical circulator; SMF: Single Mode Fibre; EAM: Electro absorption modulator; RFA: Radio frequency Amplifier; C1: Optical coupler 1; C2: Optical coupler 2; WSS: Wavelength selective switch; PD: Photodiode

Fig.1. Proposed schematic of OFC generation based on SBS

The input electrical field of the laser is given by

$$E_{laser} = E_0 e^{jw_0 t} \tag{1}$$

The RF signal from SBS is represented as V_{mod}sin (2πft) and it is fed to the first electro-absorption modulator (EAM1). The driving voltage given to EAM1 is 0. 11V.The same driving signal is amplified by 20dB and fed to the second EAM.

The optical output from the first EAM is given by

$$E_{out-1}(t) = E_0 e^{jw_0 t}.[(V_{mod(t)})^{\frac{1}{2}}. e^{\left(j\propto_1 f_1(mod(t))\right)}] \tag{2}$$

where f (mod (t)) = ln (mod (t))

The modulating signal is related to the modulation index(ɣ) as

$$V_{mod(t)} = (1 - ɣ) + ɣ \qquad (3)$$

The optical output from the second EAM [15] is given as

$$E_{out}(t) = E_{out-1}(t).\{(1-\gamma_2)^{\frac{1}{2}} + \left[\gamma_2 . e^{j\gamma_2 sinwt}\right]^{\frac{1}{2}} . e^{j\alpha_2 f_2 (mod(t))}\} \qquad (4)$$

Where α_1 and α_2 are the chirp factors, $ɣ_1$ and $ɣ_2$ are the modulation indices of EAM's.

Using Jacobi-Anger identity, the optical output from the second EAM can be expanded by Bessel functions as

$$E_{out}(t) = \{(1-\gamma_1)^{\frac{1}{2}} + \left[ɣ_1 . \sum_{k=-\infty}^{\infty} j^k J_k (ɣ_1) e^{jkwt}\right]^{\frac{1}{2}} . e^{\left(j\propto_1 f_1(mod(t))\right)}\}.\{(1-ɣ_2)^{\frac{1}{2}} . \quad + [ɣ_2 . \textstyle\sum_{k=-\infty}^{\infty} j^k J_k (ɣ_2) e^{jkwt}]^{\frac{1}{2}} . e^{\left(j\propto_2 f_2(mod(t))\right)}\} \qquad (5)$$

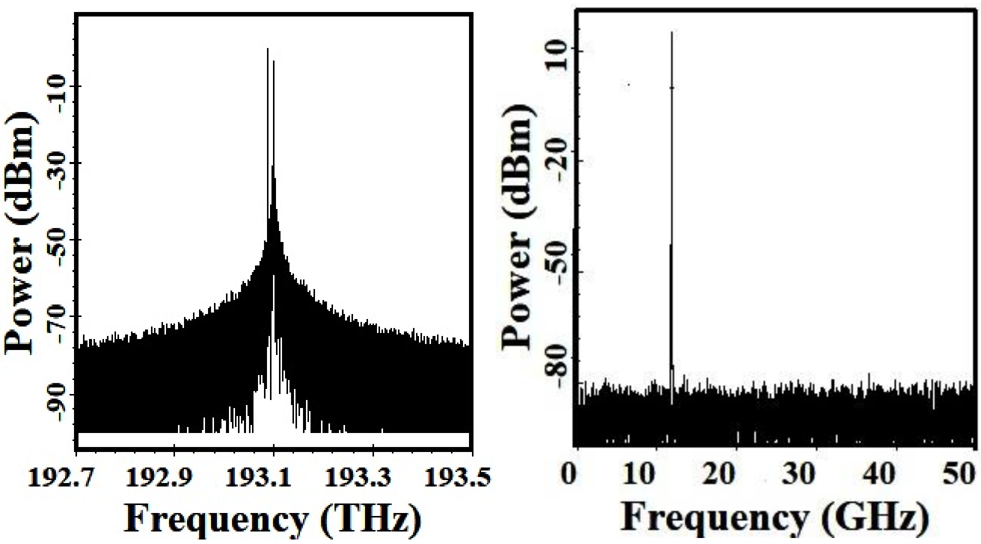
$$f\big(mod(t)\big) = \textstyle\sum_{\delta=0}^{\infty}(1/(\delta!)) f^{\delta} V_{bias} . [V sin\,(2\pi f t)]^{\delta} \qquad (6)$$

where $f^{\delta}V_{bias}$ is the δ^{th} order derivative of f (mod (t)) at $V_{mod}=V_{bias}$ f (mod (t)) can be approximated using Taylor series at DC bias, V_{bias} as [22]. Here $f_1 = f_2$=11GHz, which is due to the SBS down shift frequency. V_2 is the amplified version of the modulating signal, V_1.

Equation (5) shows the spectrum with a repetition frequency of 11GHz.The generated OFC is fed to the wavelength selective switch (WSS) for choosing the desired optical sidebands for terahertz generation. The proposed system overcomes the limitation of fixed modulating signal by utilizing the EAM to generate large number of carriers with minimal power variations.

3. Simulation results and discussion

The proposed method of SBS based OFC generation using cascaded configuration of EAM is verified by simulating it in Opti system 16 platform. A narrow linewidth DFB laser with a frequency of 193.1THz (1552.5nm), generates the optical signal at a power level of 10dBm.This signal is injected into a single Mode Fiber (SMF) through an optical circulator (OC). When the laser power exceeds the threshold, a stoke wave, which has a frequency downshift of 11GHz is produced. This stoke wave along with the pump signal is heterodyned at the photo detector (PD1) with a responsivity of 0.8A/W [27].



(a) *(b)*

Fig.2.Spectrum of (a) reflected stoke and pump signals (b) 11GHz generated at PD1

The detected 11GHz with an output power of -6dBm is used to drive the first EAM.

The second EAM is driven by the amplified version of 11GHz with a gain of 20dB.The driving RF power to the second EAM is 14dBm.

The optical spectrum at the port 3 of the optical circulator (OC) is shown in Fig. 2(a). The reflected, pump signals are heterodyned at the PD 1 and the electrical spectrum of the microwave signal at 11GHz is shown in Fig. 2(b).

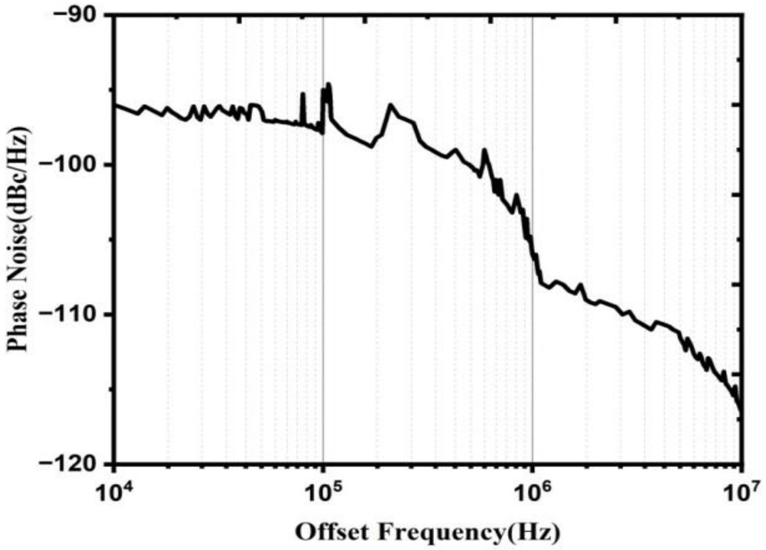


Fig.3.Phase noise for 11GHz RF signal

The phase noise of the generated RF signal was found to be -96dBc/Hz at 11GHz for a 10 kHz offset frequency as shown in Fig. 3. Fig. 4(a) shows the entire OFC spectrum with an approximate bandwidth of 1.287THz. The generated carriers with 41 comb lines within 5dB power variation are shown in Fig. 4(b). The two desired optical comb lines (192.858THz and 193.342THz) with a power of -28dBm are selected using wavelength selective switch (WSS) and it is shown in Fig. 5 (a).Fig.5(b) shows the electrical spectrum of 484GHz (0.484 THz) generated at the uni travelling carrier photodetector (InP/InGaAs UTC) with responsivity of 0.51A/W [28] having a power of -25dBm.66GHz millimeter wave with -9dBm power, is generated by selecting the comb lines, 193.067THz and 193.133THz, and is shown in Fig. 6(a). The electrical spectrum of 110GHz, mm wave with power of -15dBm, by choosing the comb lines, 193.045THz and 193.155THz, at the WSS is shown in Fig. 6(b). The phase noise characteristics of generated mm and terahertz waves are observed in Fig. 7.

The phase noise of generated millimeter and terahertz wave at 66GHz, 110GHz and 0.484THz is found to be -90dBc/Hz, -86dBc/Hz, –78dBc/Hz respectively for a 10kHz frequency offset from the carrier frequency.

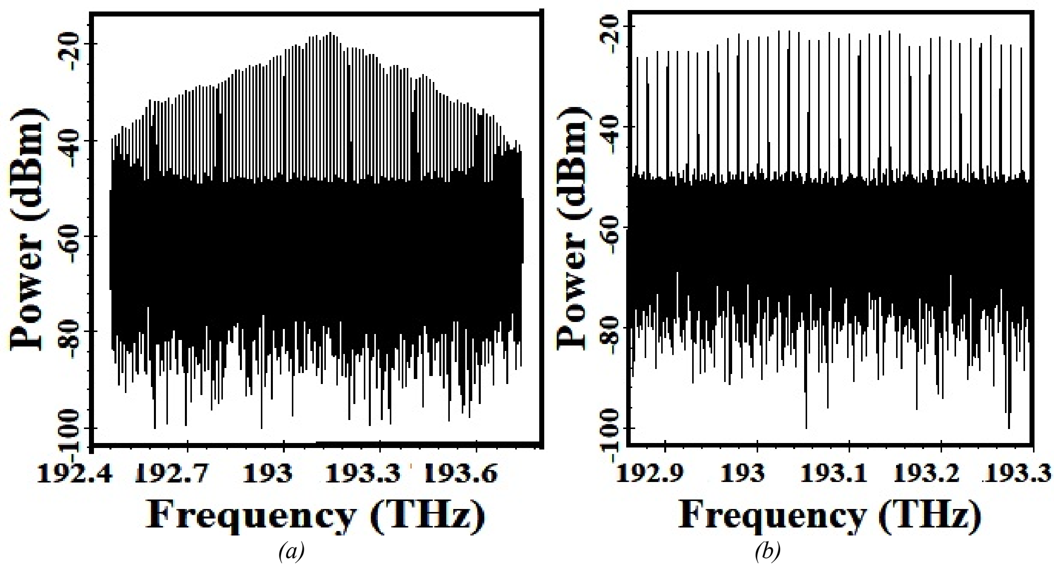
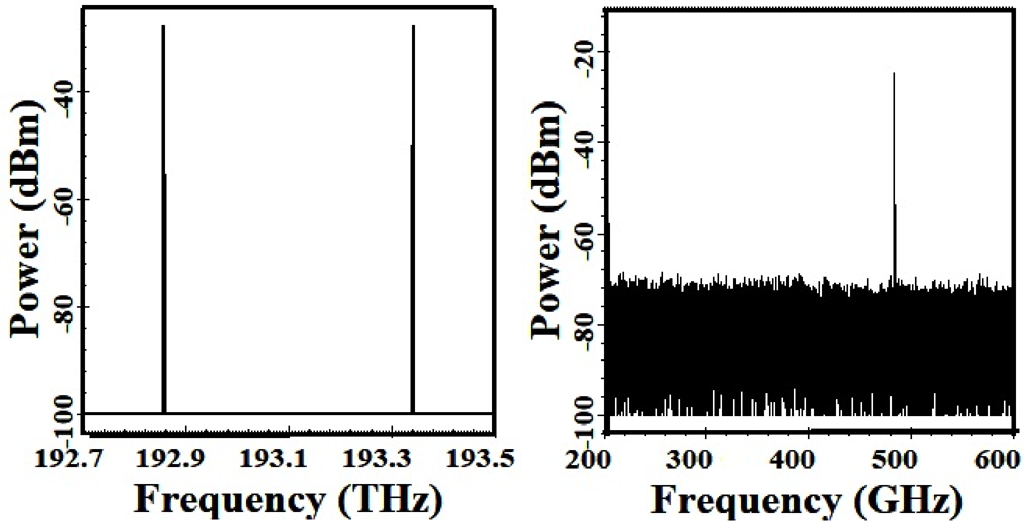
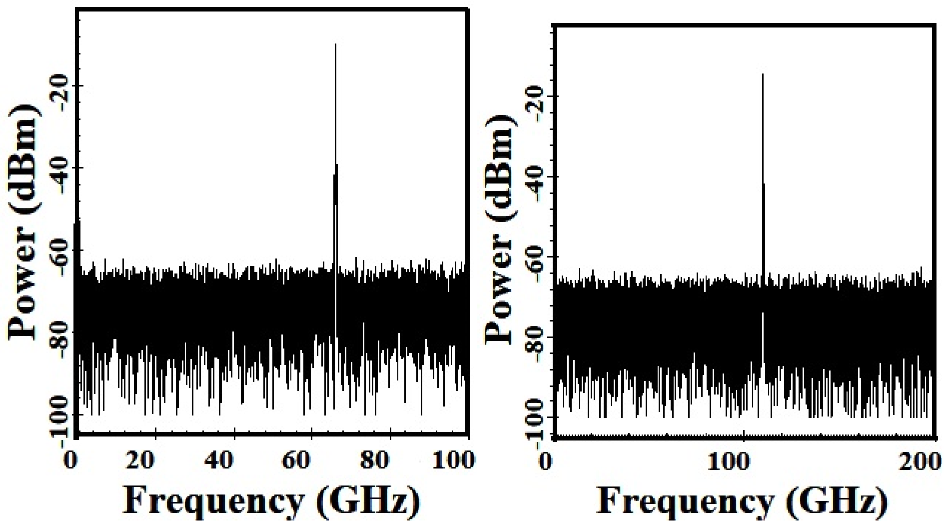


Fig. 4. (a) Spectrum of carriers with a frequency spacing of 11GHz (b) Spectrum of 41 OFC lines within 5dB power variation



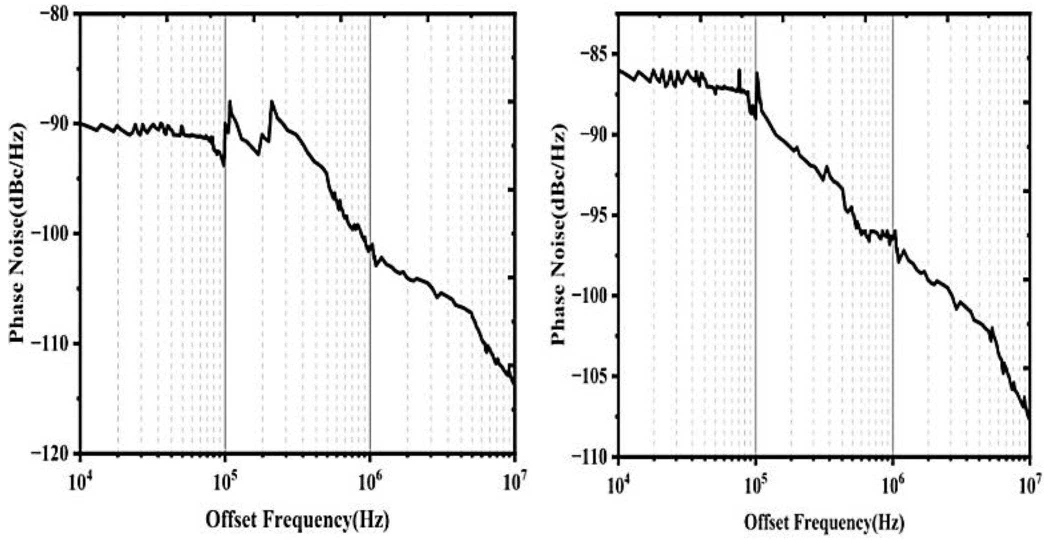
(a) (b)

Fig. 5. (a) Optical spectrum of two desired optical tones with a frequency spacing of 484GHz; (b) Electrical spectrum of 0.484THz wave

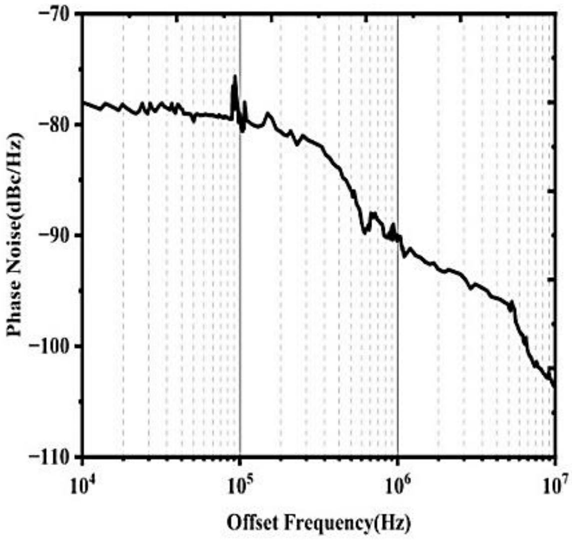


(a) (b)

Fig. 6. Electrical spectrum of generated mm waves (a) 66GHz (b) 110GHz



(a) (b)



(c)

Fig.7. Phase noise of generated mm and terahertz waves (a) 66GHz (b) 110GHz(c) 0.484THz

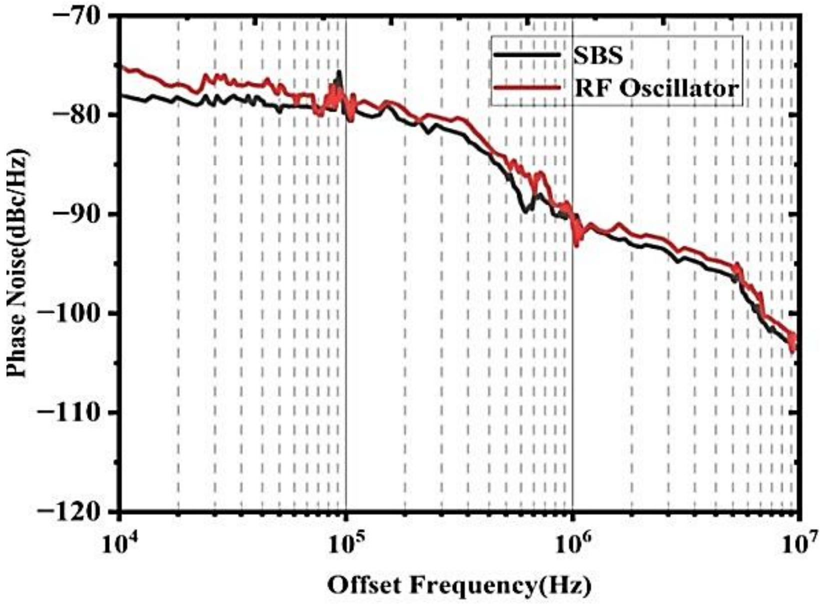


Fig. 8. Phase noise of generated tera hertz wave using SBS and RF oscillator at 0.484THz (colour online)

The phase noise of SBS and RF oscillator-based terahertz wave at 0.484THz for an offset frequency of 10 kHz is obtained as -78dBc/Hz and -75dBc/Hz respectively, as shown in Fig. 8. It can be examined that the phase noise of RF oscillator-based terahertz wave at 0.484THz is distributed over broad frequencies with respect to carrier frequency. However, SBS based phase noise seems to be distinct over certain frequencies around the Brillouin gain spectrum [32]. The frequency stability of the generated waves depends on the linewidth of the pump laser. The Brillouin gain linewidth should be less than the laser linewidth to achieve significant SBS efficiency.

The phase noise of the pump laser conveyed to stokes wave when pump power reaches the Brillouin threshold. Narrow linewidth lasers like DFB laser creates low phase noise for shorter fiber length [32]. The phase noise performance of generated millimeter and terahertz waves based on SBS is comparatively superior to the works reported in ref [30, 31].

From the Fig. 4(b), it is found that stable comb lines start from 192.858THz, which is kept fixed and tunability in generated signal is realized by varying one of the frequencies in the WSS and is illustrated in Fig. 9. Then the selected comb lines are heterodyned at the photodetector, to generate the required terahertz waves.

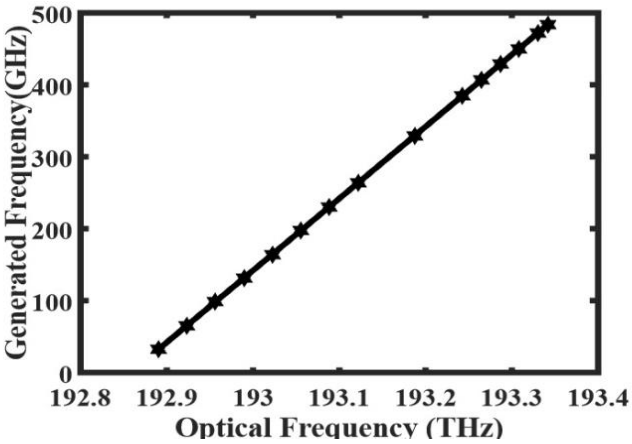


Fig. 9. Tunable generation of mm and terahertz waves

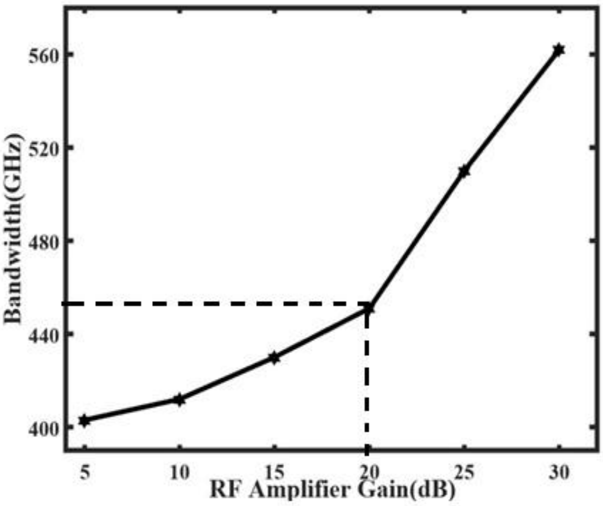


Fig. 10. Effect of amplifier gain on bandwidth of OFC within 5dB flatness

Fig.10 shows the effect of RF amplifier gain on bandwidth of OFC spectrum within 5dB power variations. At a constant pump power of 10dBm, as the modulating voltage increases due to increase in amplifier gain, the number of OFC lines further inflates. This is because drive voltage has an impact on modulation index and thereby influences the bandwidth of comb lines. With the increase of amplifier gain to 30dB, significant number of comb lines with improved flatness are achieved, hence the bandwidth is enhanced to 562GHz. However, this requires a modulating voltage of 5V to drive the EAM, which is larger than the optimum drive voltage of 1.12V. Hence an amplifier gain of 20dB is chosen, to generate 0.484THz.

The proposed method eliminates the use of electrical bandpass filter to select the desired frequency spacing. Moreover, tuning of narrow pass band over several GHz is a challenging issue in electrical domain. This bottleneck is avoided by generating modulating signal based on SBS. However, as the temperature in the devices and environment change, effective refractive index and wavelength of the pump wave will also fluctuate. Temperature, strain, and other factors will cause the Brillouin frequency shift to wander. Stimulated Brillouin scattering is a power dependent nonlinear phenomenon and it needs a constant laser power. Temperature changes and prolonged usage leads to power fluctuations [26]. The system can be stabilized by placing it in a temperature-controlled environment to address this issue. The electro absorption modulator modulates the intensity of the optical carrier by the driving signal and thereby generates new frequency components. Since two EAM's are used, maintaining same operating conditions have to be considered. The electro absorption effect usually operates close to the semiconductor material's band gap and is substantially wavelength-dependent. This also has to be considered in real time experiment. Temperature fluctuations caused by power dissipation may affect the performance of EAM. Stable operation requires efficient thermal control.

Table 1. Comparison of proposed and existing works

Cited Work	No. and Type of modulator	Type of modulating signal	Frequency Spacing	Maximum No. of carriers	Variation in power	Estimated Bandwidth	Millimeter and Terahertz wave Generation
[10]	1and DDMZM	Self-Oscillating OEO	11.84 GHz	23	-	272 GHz	No
[18]	1and PM	Self-oscillating OEO	10 GHz	10	5dB	100 GHz	No
[20]	1 and PM	raman pumped SBS based Self oscillating OEO	10.89 GHz	7	2.7dB	-	No
[21]	2 and PM	SBS based Self oscillating OEO	10.87 GHz	9	3dB	97.83 GHz	No
This Work	2 and EAM	SBS based	11 GHz	117 41	20dB 5dB	1.287THz 451GHz	Yes 66GHz, 110GHz and 0.484THz

4. Conclusion

In this paper, an approach for the tunable terahertz generation using OFC lines is put forwarded and examined by simulation. This proposal is turned on tera hertz wave generation using SBS based OFC by cascaded arrangement of EAMs. The EAM overcomes the disadvantage of fixed RF signal by generating a wideband OFC spectrum having bandwidth of 1.287THz with 117 carriers, in which 41 comb lines have flatness within 5dB. Based on this scheme, 0.484THz (484GHz) wave with a phase noise of -78dBc/Hz is generated. Moreover, generation of 66GHz, 110GHzmm wave with phase noise of -90dBc/Hz and -86dBc/Hz is also predicted by simulation.

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