

Graphene frequency tripler design using reflector networks

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Abstract: A graphene frequency tripler (GFT) is proposed. The graphene is similar to anti-parallel diodes, which has nonlinear characteristic. In order to improve the efficiency of the GFT, the output port of the GFT uses the reflector networks to recover the power of the fundamental and fifth harmonic wave. According to the mechanism, a sample GFT is designed, fabricated, and measured. In its operation frequency of 12 GHz to 30 GHz, the minimum conversion loss of -24.2 dB can be obtained at 18 GHz when the input power is 14 dBm.

Keywords: graphene, non-linear electromagnetic response, tripler, high efficiency, reflector networks

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

The microwave and millimeter wave signal sources have a variety of applications including radiometer, radar, communication and other electronic systems. Frequency multiplication is one of the popular approaches to generate the signals. In the microwave and millimeter wave band, Schottky diodes are commonly used to design the multiplier [1, 2, 3, 4]. Compared with high frequency active oscillators, the Schottky-diode multiplier is a good choice to obtain the low noise and stable frequency source [5].

In recent years, graphene, known as a two-dimensional material, has attracted lots of researchers due to its unique electrical properties, which make it very suitable for signal source applications [6]. In 2007, S. A. Mikhailov proposed that graphene has a strong non-linear electromagnetic response [7]. After that, in 2008, 2014 and 2015, S. A. Mikhailov further demonstrated its theory [8, 9, 10]. He pointed out that compared with conventional non-linear two-port devices (such as Schottky diodes), the output harmonic current of grapheme-non-linear devices dropped very slowly with the harmonic order. In addition, under the excitation of the electromagnetic wave, the output current of the graphene circuit contains only the fundamental and odd harmonic components (such as: ωt , $3\omega t$, $5\omega t$, $7\omega t$, as so on). Graphene circuits have even harmonic rejection characteristics, and are very suitable for making nonlinear devices (such as frequency multiplier, and so on).

In 2010, M. Dragoman developed a millimeter wave graphene frequency multiplier based on CPW using the nonlinear electromagnetic characteristics of graphene, and had verified the nonlinear theory of graphene firstly [11]. In 2011, R. Cambor developed a tripler using microstrip gap loaded with multilayer graphene [6]. When the input power is 20 dBm, the tripler obtained minimum conversion loss of -25.32 dB.

From the above analysis, it can be seen that, due to the strong nonlinear electromagnetic response, the output signal of the graphene circuit only contains the fundamental and odd harmonics. And the graphene circuit is very suitable for

frequency multiplier. However, the reported graphene frequency multipliers suffer from low efficiency.

This article analyzes the nonlinear characteristics of the graphene frequency tripler (GFT) firstly. Then the optimized design of the GFT's conversion loss is presented. Finally, the optimized GFT is fabricated and tested.

2 Explanation of the GFT

2.1 Analysis of the nonlinear characteristics of the GFT

The AC electric current of the non-linear behavior of graphene electrons can be expressed as Eq. (1) [7].

$$j_x(t) = en_s V \operatorname{sgn}(\sin \omega t) = en_s V \frac{4}{\pi} \left(\sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t + \dots \right) \quad (1)$$

It can be seen from Eq. (1) that the output signal of the graphene circuit contains only the fundamental and odd harmonics. Its amplitude ratio of each component is shown in Fig. 1. For the output signals, the power of the fundamental signal accounts for about 81.69%, and the power of the third harmonic signal accounts for about 9.08%, while the fifth one accounts for about 3.27%. The power of the fundamental, third and fifth harmonic signals accounts for about 94% of the total power. Therefore, in order to improve the efficiency of the frequency multiplier, recycling the power of the low-order harmonic signals is an effective way [12].

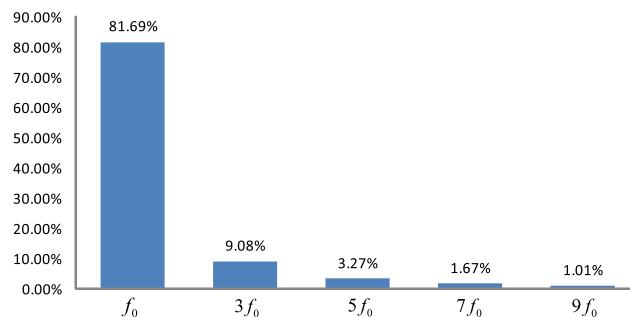


Fig. 1. Output-harmonic-signal-power ratio (graphene under electromagnetic excitation)

2.2 Optimum design of conversion loss for the GFT

In order to recover the power of the fundamental wave and the fifth harmonic signal, the topology of the proposed GFT is shown in Fig. 2a). The GFT consists of three parts: input reflector networks, multi-layer graphene, output reflector networks. The input reflector networks mainly make the third and fifth harmonic signal to ground, and the fundamental wave is grounded through the microwave source. The output reflector networks mainly recover the fundamental and fifth harmonic signal, while match the impedance of the third harmonic signal. According to the Eq. (1), and combined with graphene nonlinear electromagnetic response, there are two ways to provide GFT's working efficiency [13].

- 1) **Multiplier mode:** the third harmonic signal is generated again by the multiplying of the reflected fundamental wave signal with the output reflector networks.

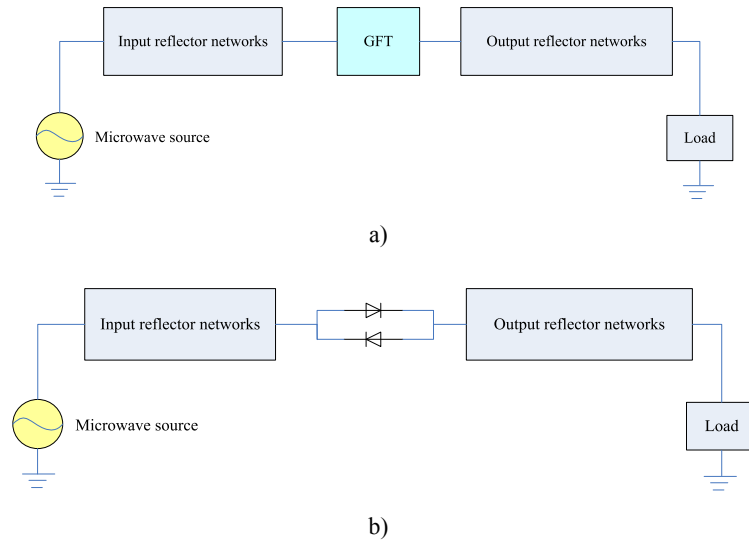


Fig. 2. Block diagram. a) GFT block diagram, b) Anti-parallel diode pair multiplier circuit

- 2) **Mixer mode:** The mixing products of the reflected fifth harmonic signal (ω_{5th}) and the fundamental signal (ω_{f0}) contain the third harmonic signal (ω_{3rd}).

The voltage of the fifth harmonic signal reflector network is $V = 2V^+ \cos \omega_{5th}t$. Where V^+ is the voltage of electromagnetic wave propagating along the positive direction, ω_{5th} is the fifth harmonic signal angular velocity, and t is propagation time. The fundamental wave can be considered as local oscillator (LO), and the reflected harmonics by the output reflector networks can be considered as RF. The voltage of LO and RF can be defined as follows:

$$V_{LO} = V_{f0} \cos \omega_{f0}t \quad (2)$$

$$V_{RF} = 2V^+ \cos \omega_{5th}t = V_{fs} \cos \omega_{5th}t \quad (3)$$

Since the amplitude of RF is much smaller than the one of LO. According to Ohm's law, the output current of the GFT can be obtained as Eq. (1).

$$j_x(t) = en_s V \operatorname{sgn}(V_{LO} + V_{RF}) \quad (4)$$

The GFT can be equivalent to an anti-parallel diode pair multiplier circuit as shown in Fig. 2b). Then the GFT-output signals contain only frequencies for $(m\omega_{f0} \pm n\omega_{fs})$ where $(m+n)$ is an odd integer [13]. Such as $m=2$ and $n=1$, and the total current of the GFT contains the third harmonic signal.

Through the multiplier mode and mixer mode, the GFT has regained the third harmonic signal. Thus the output reflector networks enhance the output power of the third harmonic signal. Fig. 3 shows the input and output reflector networks and the simulated scatter parameters using Ansoft HFSS [14].

The simulation results of the input reflector network show the return loss is higher than 10 dB in the frequency range from 7.5 to 9.5 GHz and from 17.5 to

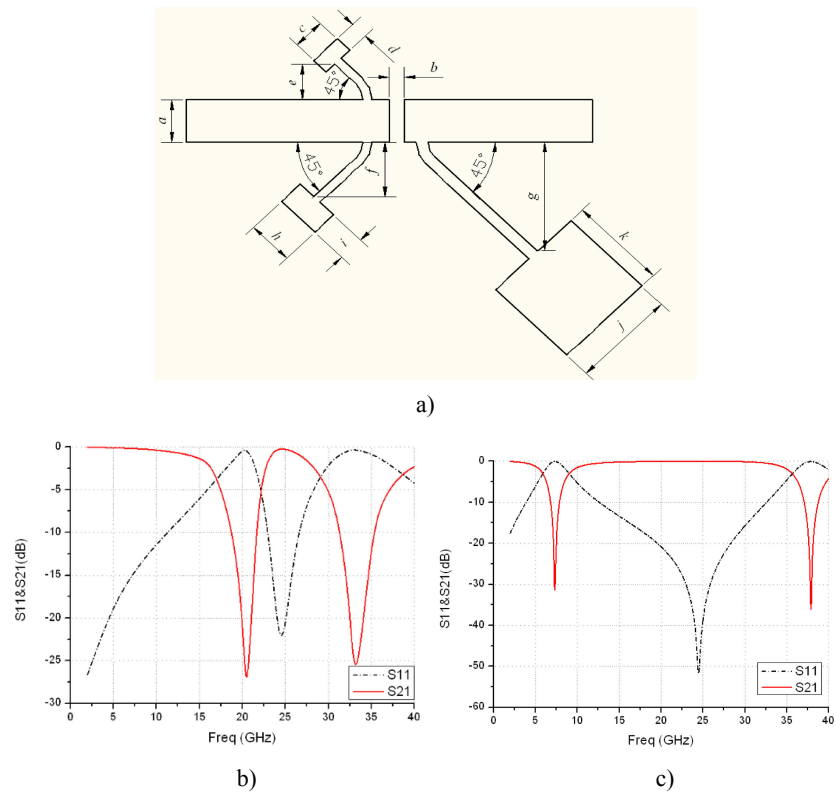


Fig. 3. GFT block diagram. a) Input/output reflector network, b) Simulated scatter parameters of the input reflector network, c) Simulated scatter parameters of the output reflector network.

19 GHz. At the same time, the return loss is lower than 0.2 dB in the frequency range from dc to 10 GHz. This means that the input reflector networks reflect the third and fifth harmonics. The simulation results of the output reflector network show the return loss is higher than 10 dB in the frequency range from 6.8 to 8 GHz and from 37 to 38.8 GHz. At the same time, the return loss is lower than 0.2 dB in the frequency range from 15 to 31 GHz. This means that the output reflector networks reflect the fundamental wave and the fifth harmonic signal. The dimensions of the GFT are shown in Table I.

Table I. Dimensions of GFT

Parameter	Size (mm)	Parameter	Size (mm)
<i>a</i>	0.78	<i>h</i>	0.8
<i>b</i>	0.35	<i>i</i>	0.45
<i>c</i>	0.57	<i>j</i>	1.8
<i>d</i>	0.3	<i>k</i>	1.7
<i>e</i>	0.65	<i>l</i>	0.15
<i>f</i>	1	<i>m</i>	0.2
<i>g</i>	2		

3 Fabrication and measurement of the tripler

According to Fig. 2 and Fig. 3, the GFT has been designed and fabricated. The sample is shown in Fig. 4. The few layer graphene film of the GFT exfoliated from highly oriented pyrolytic graphite. When the input power of 14 dBm and the output frequency is 18 GHz, the measured maximum output power of -10.2 dBm (corresponding minimum conversion loss of -24.2 dB) has been obtained as shown in Fig. 4b). The output power of the GFT without reflector networks is lower than that of the GFT with reflector networks in the frequency range from 12 to 30 GHz as shown in Fig. 4b), d) and e).

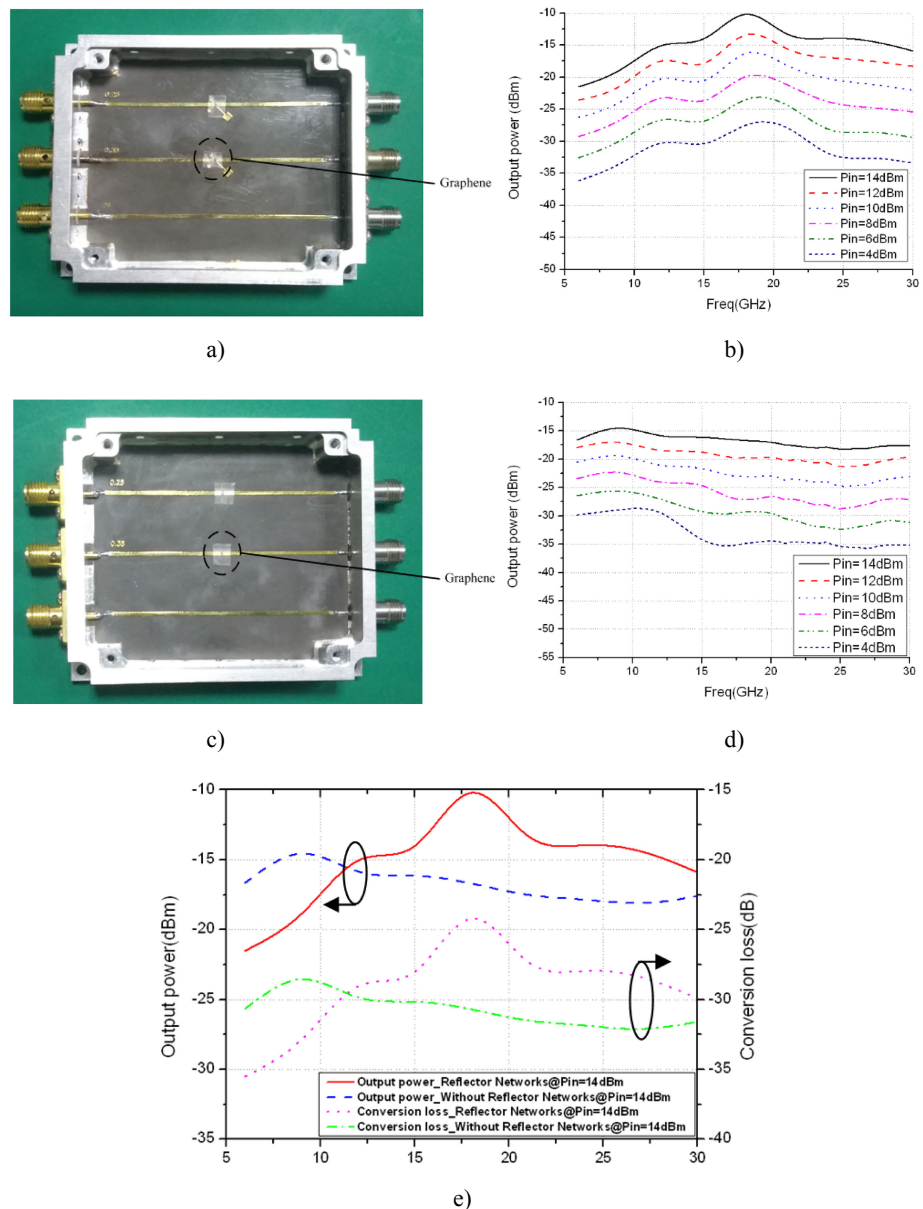


Fig. 4. Photograph of the GFT and measured curves. a) Photograph of the GFT with reflector networks, b) Output power curves with reflector networks, c) Photograph of the GFT without reflector networks, d) Output power curves without reflector networks, e) Comparison diagram of output power and conversion loss.

Table II summarizes the performances of the GFT along with previously published works. As compared with previous reported graphene multipliers, the conversion loss reduced to -24.2 dB due to the GFT using the reflector networks.

Table II. Performances summary and comparison with other graphene frequency multipliers

Ref.	Type	Harmonic order	Minimum conversion loss	Output frequency
[6]	Few layer graphene film frequency multipliers	3	-25.32 dB	15 GHz
This work	Few layer graphene film frequency multipliers	3	-24.2 dB	18 GHz

4 Conclusion

In this paper, a frequency tripler based on graphene nonlinear electromagnetic response is developed. The non-linearity of graphene is similar to that of anti-parallel diodes. The output frequency of this tripler can cover 12–30 GHz. The harmonic signals recovery using the reflector networks can significantly reduce the conversion loss. As the input power increases, the conversion loss decreases gradually, and the minimum conversion loss of -24.2 dB can be obtained at 18 GHz.

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