A broadband GaAs MMIC frequency doubler on left-handed nonlinear transmission lines*

Dong Junrong(董军荣)†, Huang Jie(黄杰), Tian Chao(田超), Yang Hao(杨浩), and Zhang Haiying(张海英)

Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China

Abstract: A broadband frequency doubler using left-handed nonlinear transmission lines (LH NLTLs) based on MMIC technology is reported for the first time. The second harmonic generation on LH NLTLs was analyzed theoretically. A four-section LH NLTL which has a layout of 5.4×0.8 mm^2 was fabricated on GaAs semi-insulating substrate. With 20-dBm input power, the doubler obtained 6.33 dBm peak output power at 26.8 GHz with 24–43 GHz −6 dBm bandwidth. The experimental results were quite consistent with the simulated results. The compactness and the broad band characteristics of the circuit make it well suit for GaAs RF/MMIC application.

Key words: GaAs; MMIC technology; LH NLTLs; frequency doubler

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1. Introduction

Veselago[1] firstly proposed left handed materials (LHMs) in 1968, which are materials with simultaneously negative permittivity (ε) and permeability (μ). LHMs have received substantial attention in the scientific and engineering communities due to their unique electromagnetic properties. Caloz[2] and Eleftheriades[3] proposed the transmission line approach of LH materials in 2002, which is a periodically laddered network of shunted inductance and series capacitance, called left-handed transmission lines (LH TLs). The majority of studies of LH TLs to date have focused on the linear regime of LH TLs and have inspired new types of microwave devices, such as antennas[4], filters[5] and directional couplers[6].

In 2004[7] and 2005[8], Alexander *et al.* discussed the nonlinear wave propagation phenomena in left-handed nonlinear transmission lines (LH NLTLs) that leads to and affects harmonic and parametric wave generation due to "anomalous dispersion". It was proposed that harmonic generation was possible over a significantly wider operating frequency range and at a relatively higher frequency in comparison with the dual conventional low-pass filter NLTL. Also, the harmonic generation had been verified experimentally on a Roger board[9]. However, the LH NLTLs were implemented by hybrid circuits, which are not suitable for RF/MMIC application.

This paper proposes a novel LH NLTL frequency doubler based on GaAs planar technology for MMIC application. The LH NLTLs frequency doubler has a layout of 5.4×0.8 mm^2 with four sections. The structures were fabricated on GaAs semi-insulating substrates with planar Schottky varactor diodes as the nonlinear series capacitor. Electroplated 2-μm-thick Au was used to form the transmission lines. 0.3-μm-thick Si_3N_4 was used to insulate the separation layers. On-wafer harmonic measurement was carried out using an Agilent E4447A PSA spectrum analyzer. With 20 dBm input power, we firstly reported that the second harmonic was generated over a 24–43 GHz band width with a maximum 6.33 dBm output power at 26.4 GHz.

2. Harmonic generation on LH-NLTLs

The equivalent circuit of the LH NLTLs is shown in Fig. 1. The L_0 is shunted inductance, C_n is the series nonlinear capacitance formed by the planar Schottky varactor diodes, R_d is the series parasitic resistance of the Schottky diode and C_0 is the constant capacitor at the input and output ports. In the linear case ($C_n = C_{j0}$) without losses ($R_d = 0$), the dispersion relation is defined as[7]:

$$\omega^2 = \frac{1}{4L_0C_{j0}\sin^2\phi/2}, \tag{1}$$

where ϕ is the phase shift per section. From the dispersion relationship, the value $\phi = \pi$ corresponds to the Bragg cutoff frequency:

$$f_B = 1/4\pi\sqrt{L_0C_{j0}}. \tag{2}$$

The harmonic generation in the LH NLTLs is qualitatively different from the harmonic generation in conventional right-handed (RH) NLTLs. Propagation of a large-amplitude sinusoid wave in RL NLTLs results in edge steeping due to the formation of a shock wave so that the spectrum of waveform at the TLs output contains higher harmonics. Shock wave formation in LH NLTLs is impossible[10]. The nonlinear and anomalous dispersion of LH NLTLs enables effective harmonic generation[8].

Based on the small signal approach ($|V_2(n)| \ll |V_1(n)|$), the amplitude of the second harmonic in the nth section of an LH NLTLs $V_2(n)$ can be obtained[10]:

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† Corresponding author. Email: dongjunrong@ime.ac.cn

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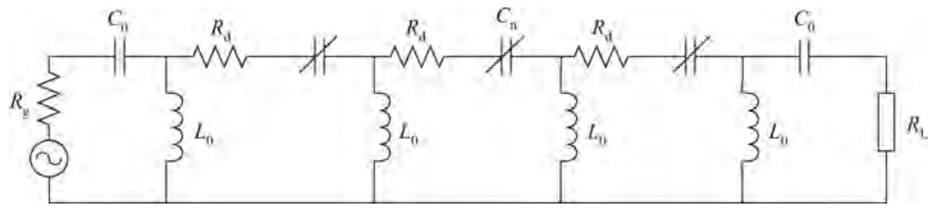


Fig. 1. Equivalent circuit of the LH NLTLs.

$$|V_2(n)| \approx \frac{4K_N V_1^2(0)\sin^2\left(\frac{\beta_1}{2}\right)\sin^2(\beta_1)}{\sin\left(\frac{\beta_2}{2}\right)\left[\sin^2\left(\frac{\beta_2}{2}\right)-\sin^2(\beta_1)\right]} \times \mathrm{e}^{-\alpha n}\cdot|\{\sin[(\beta_2-2\beta_1)n/2]\}|, \quad (3)$$

where K_N is a "nonlinearly factor" dependent only on diode parameters, $V_1(0)$ is the voltage at the input of the LH NLTLs, α is the attenuation constant, n is the section number and β_1 and β_2 are propagation constants (phase shifts) for the fundamental wave and its second harmonic, respectively. It is apparent from Eq. (3) that the maximum amplitude of the second harmonic at the end of the n-section line is achieved when:

$$(\beta_2-2\beta_1)n=(2k+1)\pi,\quad k=0,1,2,3\ldots \quad (4)$$

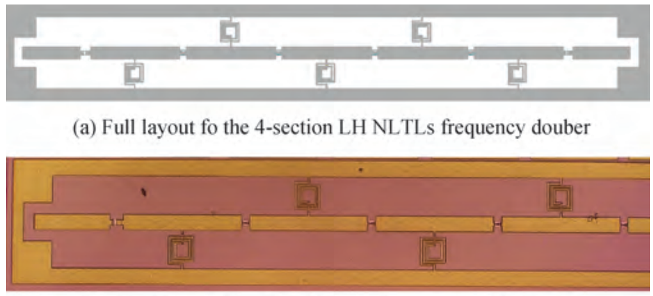
Due to the anomalous dispersion, the fundamental wave propagating in the LH NLTLs is always badly mismatched with its higher harmonics, yet the generation of higher harmonics can still be very effective. This is possible because of condition (4) and the "amplitude singularities", known as the condition $\sin^2(\frac{\beta_2}{2})-\sin^2(\beta_1)\to 0$. When the "amplitude singularities" occurred, Equation (3) is no longer valid since the condition of the small signal approximation $V_2(n)\ll V_1(n)$ is no longer met.

The harmonic generation dominates in short LH NLTLs. For longer LH NLTLs, parametric processing arises, which competes with harmonic generation. Thus, effective of harmonic generation will descend in longer LH NLTLs.

3. Experimental results

We fabricated a 4-section LH NLTL on GaAs semi-insulating substrate. It was realized based on GaAs MMIC monolithic technology. The nonlinear capacitance was formed by the GaAs planar Schottky varactor diode, the epitaxial design and the fabrication process of which were described in Ref. [11]. The shunted inductance was formed by the planar spiral inductor. The constant capacitor C_0 was realized using the MIM capacitor. The transmission lines were in the form of the co-planar waveguide (CPW). Electroplated 2-μm thick Au was used to form the planar spiral inductor, the up-board of the MIM capacitance and the transmission lines. 0.3-μm thick Si_3N_4 was used to insulate the separation layers. The total area of the LH NLTLs frequency doubler was only 5.4 × 0.8 mm^2. The layout and the photo of the circuit are shown in Fig. 2.

The capacitance characteristics of the Schottky varactor



(a) Full layout fo the 4-section LH NLTLs frequency douber

(b) The photo of the chip (three sections were only shown)

Fig. 2. (a) Layout and (b) photo of the device.

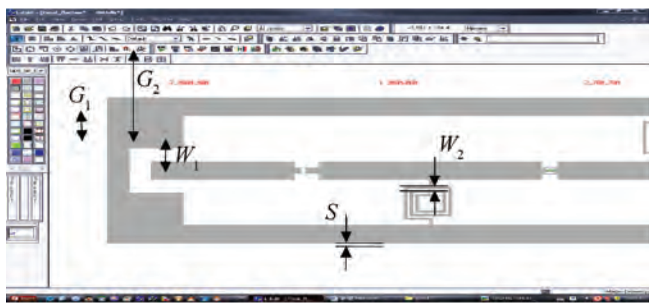


Fig. 3. Size description of the passive elements of the LH NLTL. G_1 = 250 μm, W_1 = 100 μm, W_2 = 10 μm, S = 10 μm, G_2 = 73 μm.

diode can be expressed as:

$$C_j=\frac{C_{j0}}{\left(1+\left|\frac{V}{V_{bi}}\right|\right)^M}. \quad (5)$$

For the 4-section LH NLTLs, we used C_{j0} = 124 fF, V_{bi} = 0.73 V, M = 0.4. For the shunted spiral inductor and the constant MIM capacitor, we had L_0 = 1 nH, C_0 = 0.2 pF. As shown in Fig. 3, we had the size description of the passive elements: G_1 = 250 μm, W_1 = 100 μm, W_2 = 10 μm, S = 10 μm, G_2 = 73 μm. The LH NLTL frequency doubler had the characteristic resistance $Z_0=(L_0/C_{j0})^{1/2}$ = 90 Ω, and the Bragg cutoff frequency f_B = 7 GHz. The input and output CPW ports of the LH NLTLs were matched to 50 Ω.

The S parameters were measured with an Agilent E8363B network analyzer from 0.1 to 40 GHz with –17 dBm input power, which is small enough to make the circuit operate in the linear area. Figure 4 shows the magnitude and phase of the linear wave transmission (S_{21}) of the LH NLTLs. The high-pass Bragg cutoff frequency and the dependence of phase on frequency, indicate the left-handed nature of the system. We measured an −6 dB cutoff frequency at 6 GHz, which is slightly de-

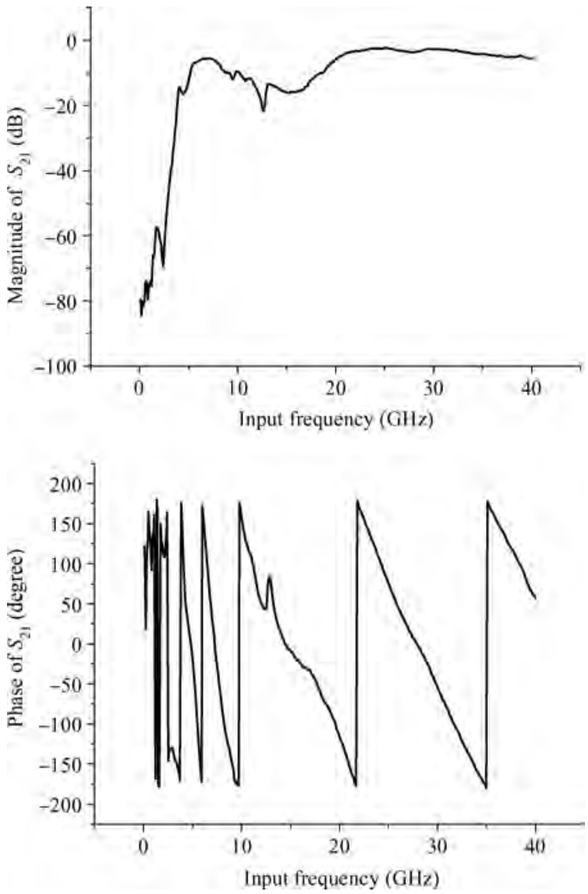


Fig. 4. Magnitude and phase of the S_{21} of the LH NLTLs.

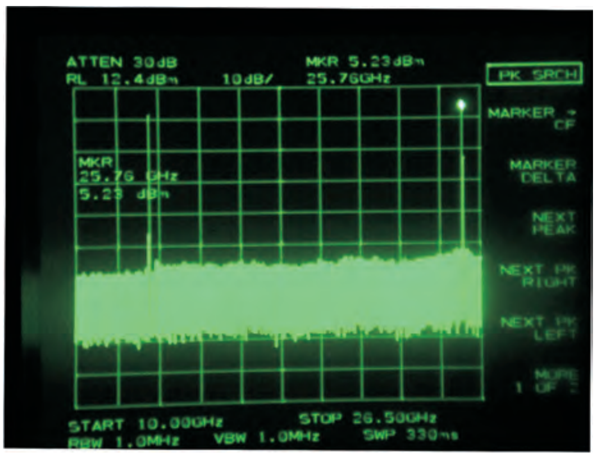


Fig. 5. Output frequency spectrum of the LH NLTL frequency doubler with 12.9 GHz input frequency.

viated from the design value of 7 GHz. It was from the result of the deviation between the actual values of the components and the correspondent design values.

The harmonic generation of the monolithic LH NLTL frequency doubler was measured on wafer using a synthesized microwave source and an Agilent E4447A PSA frequency spectrum analyzer, whose calibrations were verified with a precision power meter, the losses of the cable and probe were determined using a network analyzer. The input signals were swept from 2 to 21.5 GHz with 20 dBm constant power. The output

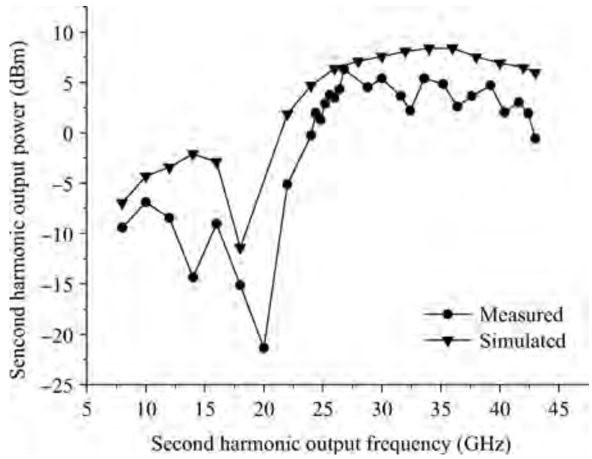


Fig. 6. Comparison of the measured and simulated second harmonic output power.

frequency spectrum with 12.9 GHz input frequency is shown in Fig. 5. The output power of the second harmonic is up to 5.23 dBm at 25.76 GHz, which is obviously higher than the fundamental wave.

Figure 6 shows the comparison of the measured and simulated second harmonic output power. The simulated results were from the harmonic balance simulation in ADS with 20 dBm input power from 2 to 21.5 GHz. The model of the varactor in this work used the large signal model of the planar Schottky diode described in Ref. [11]. The passive structures, the CPW transmission lines and the spiral inductor, were processed with high frequency full-wave electromagnetic field simulation up to 45 GHz in HFSS. The HFSS' simulated scatter parameters were imported and synthesized with the input and output ports and the varactor model in ADS to form the circuit model of the LH NLTLs. The constant capacitor C_0 used the capacitor model from the ADS's database.

The second harmonic of the LH NLTLs obtained a 6.33 dBm peak output power at 26.8 GHz, corresponding to 4.3% conversion efficiency. It observed a 24–43 GHz –6 dB bandwidth, corresponding to > 1% conversion efficiency. The measured results were in reasonable agreement with the simulated results. The lower-than-predicted second harmonic output power arise from the thermal losses of the parasitic series resistance and skin-effect losses of the transmission lines and planar spiral inductor. As shown in Fig. 6, the downtrend of the output power of the second harmonic from 10 to 20 GHz resulted from the second maximum of the amplitude of the second harmonic at 10 GHz, corresponding to the "amplitude singularities" $\sin^2(\frac{\beta_2}{2}) - \sin^2(\beta_1) \rightarrow 0$, and the local minimum at 20 GHz, corresponding to the condition (4) minimum $((\beta_2 - 2\beta_1)n = 2k\pi)$. The total size of the chip is only 5.4 × 0.8 mm^2, which is more compact than the LH NLTL harmonic generator[9, 10], which was realized on Rogers boards and was non-integrated. In this paper, the LH NLTL frequency doubler was firstly fabricated on GaAs substrate based GaAs MMIC planar technology, which considerably reduced the size of the doubler and caused it to be integrated. Therefore the circuit will be well suit for GaAs RF/MMIC application.

Simon analyzed numerically and analytically that the composite right/left-handed transmission nonlinear transmission

Table 1. State of the art for frequency doubler on NLTLs.

Parameter	Type	Section	Bandwidth (GHz)	Minimum conversion loss (dBm)
This work	Left-handed	4	24–43	13.67
Ref. [13]	Right-handed	10	28–39	17.3
Ref. [13]	Right-handed	20	27–36	19.3

lines as a frequency doubler had a broader operating bandwidth for a lower number of diodes compared with the RH-NLTL doubler in 2009[12]. However, they had not validated this experimentally. This work proved the advantages of the LH NLTL frequency doubler. The comparison is shown in Table 1.

4. Conclusion

For the first time, a broadband left-handed nonlinear transmission line frequency doubler based MMIC planar process has been fabricated. The LH NLTL frequency doubler with a 5.4×0.8 mm^2 chip area is more compact and has lower losses in comparison with the LH NLTLs by hybrid circuit[9, 10]. It had an almost 20-GHz-wide operating frequency range and the operating frequency was up to 43 GHz. The highest measured second harmonic output power was up to 6.33 dBm at 26.8 GHz, corresponding to 4.3% conversion efficiency. In summary, we have demonstrated millimeter wave distributed LH NLTL frequency multiplication on a monolithic GaAs device. The integration and broad band make it well suit for GaAs RF/MMIC application.

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