第33卷第1期
2014年2月

红外与毫米波学报
J. Infrared Millim. Waves

Vol. 33, No. 1
February, 2014

文章编号: 1001-9014(2014)01-0062-06

DOI: 10.3724/SP.J.1010.2014.00062

Design and microfabrication of folded waveguide circuit for THz TWT

WANG Ya-Jun[1,2], CHEN Zhang[1,2], CHENG Yan-Lin[1], SHI Zhi-Gui[1]

(1. Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang, Sichuan 621900, China;
2. Terahertz Research Center, China Academy of Engineering Physics, Mianyang, Sichuan 621900, China)

Abstract: A simple method based on the physical characteristics to get the main parameters of folded waveguide traveling wave tube (TWT) circuit is presented. Providing the operating frequency and beam voltage, the authors can obtain the initial structural parameters of the FWTWT. A D-band folded waveguide circuit was used to verify this method. The cold characteristics including dispersion relation and interaction impedance were analyzed. The simulation results show good agreement with their theory formula analysis. The folded waveguide slow-wave structure has flat dispersion relation, fairly high interaction impedance about 3.5 ohms at the center frequency of 220 GHz. The large signal performance of 27 mm (50 periods) folded waveguide circuit was predicted. Simulations show the nonlinear gain is 13.5 dB at 220 GHz where beam voltage and current are 20.6 kV and 15 mA, respectively. A saturated 3 dB bandwidth is 11 GHz (213 ~ 224 GHz). The Microfabrication process to produce the folded waveguide circuits was discussed. The first example of the folded waveguide circuit was fabricated by UV-LIGA process.

Key words: TWT; folded waveguide; simulation; UV-LIGA; terahertz radiation
PACS: 84.40.Fe

太赫兹折叠波导慢波结构的设计与微加工

王亚军[1,2], 陈 樟[1,2], 程焰林[1], 施志贵[1]

(1. 中国工程物理研究院,电子工程研究所,四川 绵阳 621900;
2. 中国工程物理研究院,太赫兹研究中心,四川 绵阳 621900)

摘要: 从行波管工作的物理特性提出了一种获得折叠波导慢波结构参数的简单方法,给定工作频率和电压,能够获得折叠波导慢波结构的初始参数.设计了D波段的折叠波导结构来验证该方法,对其冷测特性如色散、耦合阻抗进行了分析.仿真结果表明,设计的折叠波导慢波结构在中心频率处具有较平缓的色散关系,在中心频率处耦合阻抗为3.5欧姆.在电子注电压为20.6 kV,电流为15 mA时,27 mm(50个周期)的折叠波导慢波结构在220 GHz具有13.5 dB的增益,3 dB带宽为11 GHz (213 ~ 224 GHz).同时讨论了折叠波导慢波结构的微加工工艺,并通过UV-LIGA工艺获得了实验样品.

关 键 词: 行波管;折叠波导;仿真;UV-LIGA;THz辐射
中图分类号: TN129 **文献标识码**: A

Introduction

The THz radiation wave with a frequency of 0.1 THz to 10 THz, is of importance in varieties of applications to high-rate communications, space research, radar and remote sensing, and so on, which require high-power, reliable, compact, efficient and relatively inexpensive sources. Semiconductor based sources, such as quantum cascade laser, Gunn and IMPATT diodes, or typical fast wave vacuum electron devices such as free electron lasers, do not presently seem capable of providing simultaneously the high-pow-

Received date: 2012-11-12, **revised date**: 2013-06-13 **收稿日期**: 2012-11-12, **修回日期**: 2013-06-13
Foundation items: Supported by Advance Research Program of China Academy of Engineering Physics.
Biography: Wang Ya-Jun (1984-), male, Mianyang, Sichuan, master. Research area involves Terahertz vacuum electron devices. E-mail: yjwang01@163.com.

er, high efficiency and high bandwidth[1]. Micro-machined vacuum electron devices, that is, micro-VEDs represent a promising solution[2-3]. As the operation frequency increases up to terahertz, the traditional machining is not feasible for processing requirements. Recent developments in microelectromechanical systems (MEMS) technologies make it possible to miniaturized high frequency vacuum electron devices[4-5]. Compared with helix TWT[6] and coupled cavity TWT[7], folded waveguide TWT is one of the most practical and promising terahertz-range source because of its tremendous advantages. It has high-power, moderate bandwidth, and robust all-metal structure. Also, the folded waveguide can be fabricated by micro-machined technology, making it easy to fabricate, and relative low cost and high reproducibility. Further, the waveguide transitions can be fabricated with the folded waveguide circuit at one time. Therefore, in recent years, many studies have been focused on this kind of slow-wave structure for the TWT[8-9]. Many novel folded waveguide circuit are studied for improvement of the gain and bandwidth [10-12].

For the folded waveguide TWT system, the folded waveguide slow-wave structure is one of the most important components. In this paper, we design a 220 GHz folded waveguide circuit for wireless high-rate communications system, which can enhance the communication distance greatly. Based on the physical characteristics of folded waveguide slow-wave structure, we derived a simple method to get the main parameters of the folded waveguide circuit. The cold characteristics of optimized structural parameters of the folded waveguide circuit, including dispersion relation and interaction impedance were analyzed using high frequency structure simulator (HFSS). Large signal performance of the folded waveguide circuit was predicted by the CST particle studio. The UV-LIGA process of the folded waveguide circuit has also been discussed.

1 Design of the folded waveguide circuit

Fig. 1 is the schematic of the folded waveguide circuit. It is formed by E-plane bends rectangular serpentine waveguide and the beam tunnel hole in the broad wall of the rectangular waveguide. a and b is the width and height of the transverse rectangular waveguide, respectively. h is the length of straight waveguide. w is the width of the electron beam tunnel, R_{avg} is the average radius of E-plane bending. p is the length of one pitch (half period). In contrast to general periodic structures, such as the coupled-cavity structure and the helical structure, the axial phase velocity of an electromagnetic wave in the folded waveguide is slowed down to the velocity of an electron beam by its periodic nature. Because of the two-dimensionality of the MEMS process, it sacrifice beam-wave impedance a little with a rectangular beam tunnel instead of a round beam tunnel[7]. In folded waveguide circuit, the structural parameters including a, b, h and p, have great effects on the dispersion relation and interaction impedance. It is difficult to design an optimum folded waveguide circuit to meet the specifications, such as gain, bandwidth and power. In this paper, we try to derive a simple method to get the main parameters of the folded waveguide circuit based on physical characteristics.

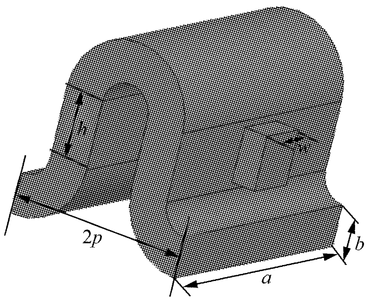

Fig. 1 The schematic of the folded waveguide circuit
图 1 折叠波导电路结构示意图

It is assumed that a TE_{10} mode is propagated along the waveguide, and the mode structure is not changed. The analytic dispersion relation of the folded waveguide circuit in half geometric period p is

$$\omega^2 = \omega_c^2 + \frac{p^2c^2}{(h+\pi p/2)^2}\left(\beta_m - \frac{2m+1}{p}\pi\right)^2 \quad ,(1)$$

where ω_c is the cutoff angular frequency, β_m is the on-axis phase constant of the m_{th} spatial harmonics, $\beta_m p = \beta_0 p + 2\pi m$, and $m = 0, \pm 1, \pm 2 \cdots$

At center frequency $\omega = \omega_0$, the propagation constant of the zero spatial harmonic β_0 should match that of the slow space charge wave in the electron beam[13]

$$\beta_e + \beta_p = \beta_0 \quad , \quad (2)$$

where $\beta_p = \omega_p / \nu_b$, $\beta_e = \omega / \nu_b$, ω_p is the plasma angular frequency and ν_b is the electron beam velocity. In the THz range, $\omega_p \ll \omega$, β_p is neglected, we get

$$\beta_e = \beta_0 \quad . \quad (3)$$

It avoids inputting the initial parameters such as beam voltage I_0 and radius of beam r_e for getting the initial structure parameters of folded waveguide circuit[14]. The beam current I_0 can be gotten by taking into account the efficiency and specifications.

Taking into account the relativistic effect, the electron velocity is

$$\nu_b = c\sqrt{1 - \left(\frac{511}{511 + U_0}\right)} \quad , \quad (4)$$

where U_0(kV) is the beam voltage.

Changing the analytic dispersion relation (1) to the other form

$$\frac{v_p}{c} = \frac{p}{h + \pi p/2} \frac{1}{\sqrt{1 - (f_c/f)^2} + \frac{c}{2f(h + \pi p/2)}} \quad . \quad (5)$$

When the rate of change of v_p/c is zero, the dispersion curve will be flatter and the bandwidth of a folded waveguide TWT will be large, the operation frequency will be near this point. Then derivative of v_p/c and setting it equal to zero, we get

$$h + \pi p/2 = a\sqrt{(f_0/f_c)^2 - 1} \quad . \quad (6)$$

According to Floquet theorem, we can derive the analytic formula of interaction impedance, given as follows.

$$K_c = Z_0\left[\frac{1}{\beta_m p}\frac{\sin\beta_m b/2}{\beta_m b/2}\right]^2 \quad , \quad (7)$$

where Z_0 is the characteristic impedance of TE_{10} mode.

Differentiating (7) with respect to b and set the expression equal to zero, we get

$$\beta_0 b = 2.3311 \quad . \quad (8)$$

Then K_c has a maximum.

A value of f_0/f_c of 1.25 was selected as a good compromise with respect to gain, bandwidth and backward wave oscillation (BWO)[15]. Through the above formulas, we can get the initial structural parameters of the folded waveguide circuit. The width of the rectangular beam tunnel can be gotten by tradeoff the bandwidth and output power. However the interaction impedance of the folded waveguide circuit by this method is small and it needs larger current to get the required gain, although the bandwidth of folded waveguide is large. In order to tradeoff the bandwidth and gain, we reduce the cold bandwidth by shortening the value a, and set the phase shift of the center frequency at 1.47π. Table 1 is the initial and optimized structural parameters of the folded waveguide circuit.

Table 1 The initial optimized structural parameters of folded waveguide circuit

表1 设计的折叠波导结构参数

Structural parameters	initial (mm)	optimized (mm)
a	0.852	0.8
b	0.137	0.12
h	0.202	0.2
w	–	0.16
p	0.289	0.27

2 Simulations of the folded waveguide circuit

Using HFSS, we set up the geometric model of folded waveguide with electron beam tunnel, as shown in Fig. 1. Fig. 2 shows a normalized phase velocity as a function of frequency, ranging from 195 GHz to 250 GHz. HFSS simulation is used to compare with the equivalent circuit model of folded waveguide[16]. As shown in Fig. 2, the results of HFSS simulation are in good agreement with the results of the equivalent circuit model. It shows that the beam tunnel and circuit bends have a smaller effect on the dispersion relation. The folded waveguide structure has a fairly flat dispersion around 220 GHz.

Interaction impedance is another important characteristic parameter. It shows the interaction strength

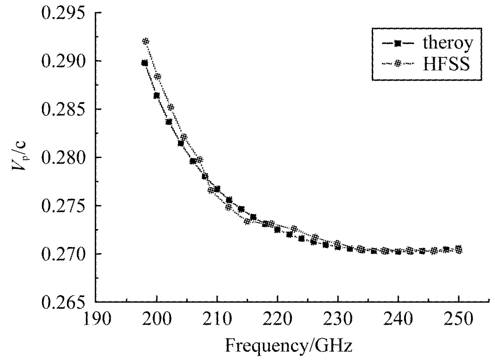

Fig. 2 Normalized phase velocity

图2 归一化相速

between beam and wave. And gain is proportional to interaction impedance. Fig. 3 shows the interaction impedance as a function of frequency. The simulation is in agreement with theory calculation. As shown in Fig. 3, interaction impedance is decreased rapidly as the frequency increased. As the frequency moves away from the cutoff frequency, interaction impedance maintains nearly constant. The interaction impedance is about 3.5 ohms in 220 GHz.

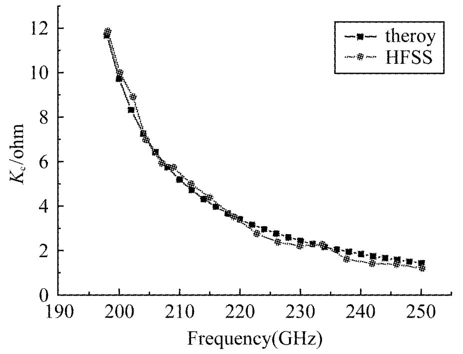

Fig. 3 Interaction impedance
图3 互作用阻抗

The nonlinear large signal numerical simulations of folded waveguide slow-wave structure are analyzed by CST particle studio. Fig. 4 shows the simulation model of 50 periods of folded waveguide. The simulation model was comprised of the folded waveguide and beam current emitter. The beam voltage is 20.6 kV. The beam current is 15 mA, and the filling rate of the beam tunnel is 50%. The beam is focused by conventional period permanent magnet (PPM) and the value is 0.3 T. The input signal is a monofrequent sinus with an input power of 10 mW. Considering the surface roughness of microfabricated folded waveguide circuits, we assume the conservative effective wall conductivity of copper is 4×10^7 Simens/m.

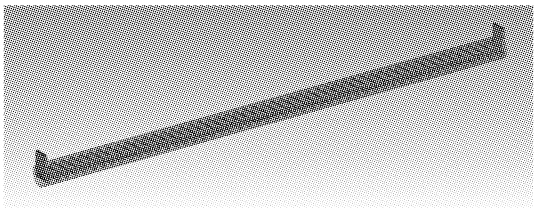

Fig. 4 The simulation model of 50 periods of folded waveguide
图4 折叠波导仿真模型

In order to gain an instantaneous bandwidth, different input frequencies were simulated. Fig. 5 shows the large signal gain as a function of driving frequency using CST. As shown in Fig. 5, the power gain is found to be 13.5 dB at 220 GHz, and 3 dB bandwidth of 11 GHz (213 ~ 224 GHz).

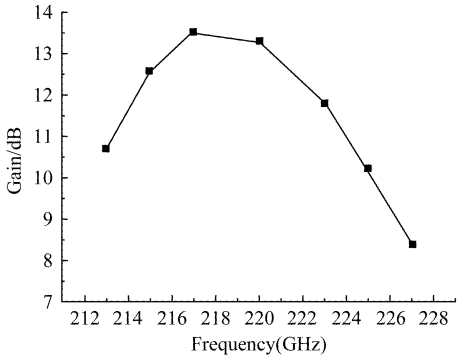

Fig. 5 Gain as a function of driving frequency using PIC code
图5 增益随频率的关系

3 UV-LIGA fabrication

A major challenge in realizing folded waveguide TWT is the fabrication of the folded waveguide circuit. Recently, there have been intensive efforts to employ LIGA technology[17] and deep reactive ion etching (DRIE)[18] to fabricate the folded waveguide circuit. However, The LIGA technology is expensive and it needs more time to fabricate the mask. DRIE technology is a process for silicon. The silicon structures serve as a mold itself for generating metallic structures, or must be metalized. UV-LIGA using SU-8 is another alternative technology for fabricating the folded waveguide circuit. It can gain high high-aspect ratio structure, vertical sidewalls, and it is inexpensive and timesaving. The completed folded waveguide circuit is an all-copper structure, providing efficient cooling needed for a high-power RF circuit.

The process of folded waveguide is shown in Fig. 6. First, a 315 μm thick SU-8 was spun on the Cu substrate. This photoresist layer was exposed and developed to define the circuit geometry without a beam tunnel. Cu was electroplated around the SU-8 mold forming the folded waveguide. Then polishing the surface using CMP, the second SU-8 layer was spun on the substrate. After exposed and developed SU-8, another layer of Cu was electroplated for forming a beam tunnel. Then the planarization was followed by polishing, and SU-8 was eliminated. By aligned bonding of two mirrored cell, we get the folded waveguide circuit.

In the UV-LIGA process, there are few challenges to be overcome. First, the folded waveguide structure required vertical sidewalls, which are difficult to obtain in negative-tone resists. There are 10 μm differences between the top and the bottom of resist in process. Second, the adhesion is weak between SU-8 resist and copper substrate. Another, because of the internal stress accumulated in post exposure bake, it lead to adhesion failure during or after development. In order to avoid it, the copper substrate is oxidized in 200 ℃. Third, The SU-8 resist is very difficult to remove. We adopt the molten salt bath to complete remove the SU-8 photoresist in the MEMS laboratory of Shanghai Jiao Tong University.

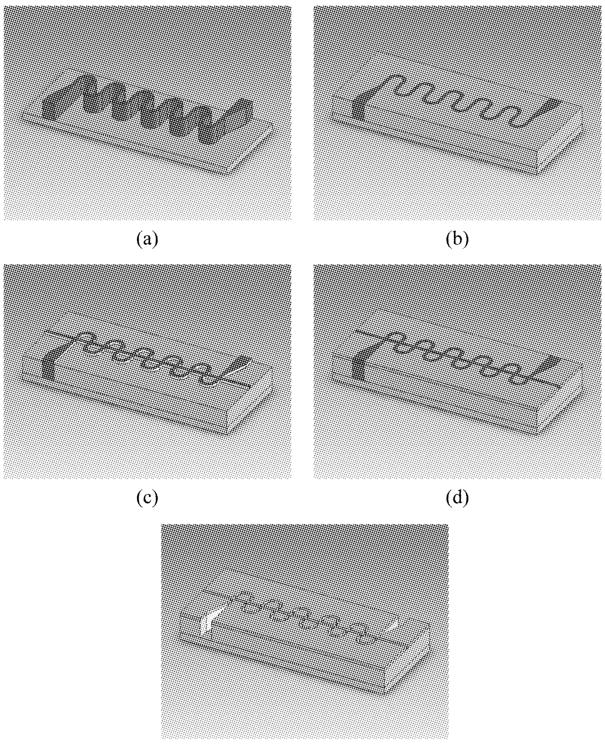

Fig. 6 UV-LIGA fabrication sequence of folded waveguide circuit. (a) Spin and exposure SU-8 in copper base; (b) Electroplating; (c) Spin and exposure second SU-8; (d) Electroplating; (e) Elimination of SU-8
图6 折叠波导结构的 UV-LIGA 工艺流程. (a)旋涂、曝光 SU-8 胶;(b)电镀;(c)第二次旋涂、曝光 SU-8 胶;(d)电镀;(e)去除光刻胶

Figure 7 is the SEM of an SU-8 mold of a folded waveguide. The SU-8 folded waveguide is about 300 μm thickness. This shows a negative image of a circuit. We can get the folded waveguide TWT circuits used SU-8 as a mold. The first example of folded waveguide circuits with waveguide transitions microfabricated by the UV-LIGA process is shown in Fig. 8. The folded waveguide circuit has a rectangular beam tunnel. Optimization of the UV-LIGA processing to achieve the desired dimensional tolerances is in progress.

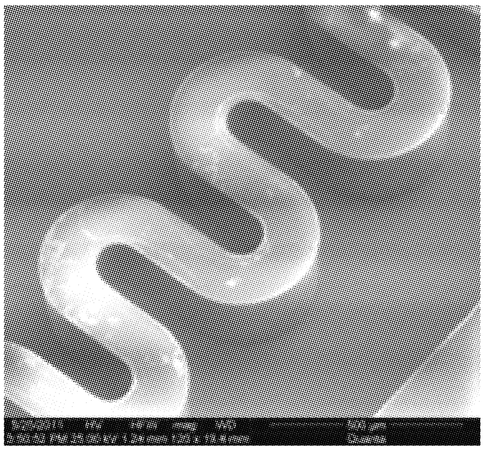

Fig. 7 SEM views of an SU-8 mold of a folded waveguide
图7 折叠波导结构 SU-8 胶膜扫描电镜照片

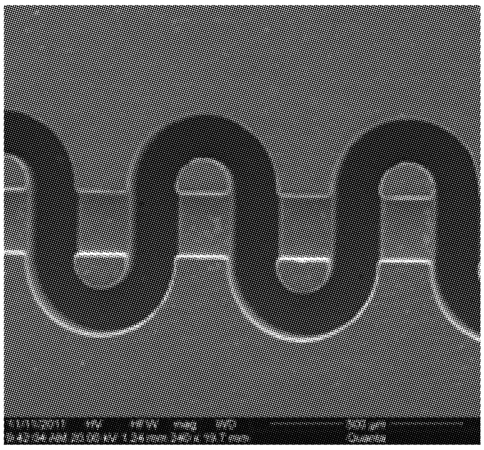

Fig. 8 SEM views of UV-LIGA produced folded waveguide circuit
图8 UV-LIGA 制作的折叠波导结构扫描电镜图片

4 Conclusions

A simple method based on the physical characteristics to get the main parameters of the folded waveguide circuit is presented. With the knowledge of the operating frequency and beam voltage, we can obtain the initial structural parameters of the FWTWT. An optimized structure of 220 GHz folded waveguide slow-wave structure was designed in order to tradeoff the bandwidth and gain. Cold characteristics of a folded waveguide circuit including dispersion relation and interaction impedance were calculated using HFSS. The simulative values have good agreement with the theory ones. The large signal performance was predicted by PIC code. The nonlinear simulation shows that gain is 13.5 dB at 220 GHz, and 3 dB bandwidth of 11 GHz (213 ~ 224 GHz). The micromachined process of the folded waveguide circuit has been discussed. The first example of folded waveguide circuits was fabricated by UV-LIGA. Optimization of the UV-LIGA processing to achieve the desired dimensional tolerances was discussed. In order to eliminate regenerative oscillations, attenuator for a folded waveguide TWT is important. In THz TWT, the traditional BeO attenuator isn't fabricated because of its size. DRIE-machined Si attenuator shows promise as drop-in components for THz TWT. The design and DRIE fabrication of Si attenuator is in progress.

REFERENCES

[1] Booske J H, Kory C L, Gallagher D, *et al*. Terahertz-regime, micro-VEDs: evaluation of micromachined TWT conceptual designs[C]. IEEE PPPS2001, USA: Las Vegas, 2001: 17-22.

[2] Ives R L. Microfabrication of high frequency vacuum electron devices[J]. *IEEE Trans. Plasma Sci*, 2004, **32**(3): 1277-1291.

[3] Han S T, Jeon S G, Shin Y M, *et al*. Experimental investigations on miniaturized high-frequency vacuum electron devices[J]. *IEEE Trans. Plasma Sci*, 2005, **33**(2): 679-684.

[4] Song J J, Decarlo F, Kang Y W, *et al*. MM-wave cavity/klystron developments using deep x-ray lithography at the advanced photon source[C]. APAC1998, Japan: Tsukuba, 1998: 298-300.

[5] Han S T, So J K, Jang K H, *et al*. Investigations on a microfabricated FWTWT oscillator[J]. *IEEE Trans*. Electron Devices, 2004, **52**(5): 702-708.

[6] Kory C L, Dayton J A, Mearini G T, *et al*. 95 GHz helical TWT design [C]. IVEC2008, USA: Monterey, 2008: 125-126.

[7] Shin Y M, Park G S, Scheitrum G P, *et al*. Novel coupled-cavity TWT structure using two step LIGA fabrication[J]. *IEEE Trans. Plasma Sci*, 2003, **31**(6): 1317-1324.

[8] Feng Jin-Jun, Hu Yin-Fu, Cai Jun, *et al*. Progress of W-band 10W CW TWT[C]. IVEC2010, USA: Monterey, 2010: 501-502.

[9] Tucek J, Basten M, Gallagher D, *et al*. 220 GHz folded waveguide circuits for high power amplifiers [C]. IVEC2009, Italy: Rome, 2009: 108-109.

[10] He Jun, Wei Yan-Yu, Gong Yu-Bin, *et al*. Linear analysis of a W band groove-loaded folded waveguide traveling wave tube[J]. *PHYSICS OF PLASMAS*, 2010, **17**(11): 113305.

[11] He Jun, Wei Yan-Yu, Gong Yu-Bin, *et al*. Investigation on a W band ridge-loaded folded waveguide TWT[J]. *IEEE Trans. Plasma Sci*, 2011, **39**(8): 1660-1664.

[12] Gong Yu-Bin, Yin Hai-Rong, Yue Ling-Na, *et al*. A 140-GHz two-beam overmoded folded-waveguide Traveling-Wave Tube[J]. *IEEE Trans. Plasma Sci*, 2011, **39**(3): 847-851.

[13] Liu Sheng-Gang, Li Hong-Fu, Wang Wen-Xiang, *et al*. Introduction to microwave electronics[M]. Beijing: National defense industry press, 1985: 413-415.

[14] Han S T, Kim J I, Park G S. Design of a folded waveguide traveling-wave tube[J]. *Microw Opt Tech Lett*, 2003, **38**(2), 161-165.

[15] Dohler G, Gagne D, Gallagher D, *et al*. Serpentine waveguide TWT [C]. IEDM1987, USA: Washington, 1987: 485-488.

[16] Booske J H, Converse M C, Kory C L, *et al*. Accurate parametric modeling of folded waveguide circuits for millimeter-wave traveling wave tubes[J]. *IEEE Trans. Electron Devices*, 2005, **52**(5): 685-694.

[17] Shin Y M, So J K, Han S T, *et al*. Microfabrication of millimeter wave vacuum electron devices by two-step deep-etch x-ray lithography[J]. *Appl. Phys. Lett*, 2006, **88**: 16-19.

[18] Tucek J, Gallagher D, Kreischer K. A Compact, high power, 0.65 THz source[C]. IVEC2008, USA: Monterey, 2008: 16-17.

(上接 54 页)

[9] Graf A, Arndt M, Sauer M, *et al*. Review of micromachined thermopiles for infrared detection [J], *Measurement Science and Technology*, 2007, 18: R59-R75.

[10] Chen Er-Zhu, Liang Ping-Zhi. Infrared microbolometer of lateral polysiliconp + p-n + junction based on standard CMOS process[J]. *J. infrared millim. waves*(陈二柱, 梁平治. 基于 CMOS 工艺的横向多晶硅 p^ + p^-n^ + 结红外微测辐射热计. **红外与毫米波学报**), 2005, **24**(3): 227-230.

[11] Calaza C, Viarani N, Pedretty C, *et al*. An uncooled infrared focal plane array for low-cost applications fabricated with standard CMOS technology[J]. *Sensors and Actuators A*, 2006, 132: 129-138.