COMPACT TUNEABLE MICROWAVE TERAHERTZ SOURCE

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Abstract

Recently, it has been suggested that the next generation of millimetre/terahertz wave devices should be the result of the combination of the virtues of vacuum tubes with solid-state microfabrication methods. Vacuum devices can be very efficient if what is called a depressed collector system is used, so much so that efficiencies as high as 40% are commonplace at microwave frequencies. In addition, the electron mobility is essentially infinite, whereas in a solid-state component, carrier mobility is a serious limitation and leads to device heating problems and reduced efficiency. On the other hand, solid-state fabrication methods lead to micron size accuracy, with good yields and the economy of mass production, so that it is now possible to construct the miniature vacuum electronic device components required for operation at very short wavelengths. In addition, electron guns manufactured in silicon are now available, and these operate at much lower temperatures and produce higher beam current densities than are achievable with conventional thermionic emitters. It has recently been proposed that a folded waveguide travelling wave tube could be constructed using silicon microfabrication technology. When configured as an oscillator this device could provide a high power (>100mW), highly efficient (>15%), reliable, compact and cheap source for the Terahertz Gap. This paper will present a comprehensive up to date on the current status of Liverpool John Moores University electromagnetic wave.

1 Introduction

The region of the electromagnetic spectrum, see figure 1, between about 300 and 3000 GHz (a wavelength range from 1mm to 0.1mm) appears to have exceptional potential for areas as diverse as medicine, the detection of explosives and high data rate communications [1,2]. However, a major obstacle to the exploitation of this potential is the lack of radiation sources that are sufficiently powerful (1mW to 1W), efficient (≥1%), frequency agile, reliable, compact and cheap. Semiconductor based sources, either in the form of electronic devices such as the Gunn diode, or as optical lasers such as the quantum cascade laser, do not presently seem capable of providing simultaneously the high power, high efficiency and high bandwidth required, see figure 2. Vacuum electronic devices such as the gyrotron or the free electron laser are usually large and expensive, and require very high voltage for their operation. This makes them unsuitable for many of the possible applications. As a consequence, the term Terahertz Gap is now in common uses to refer to this largely unexploited portion of the spectrum.

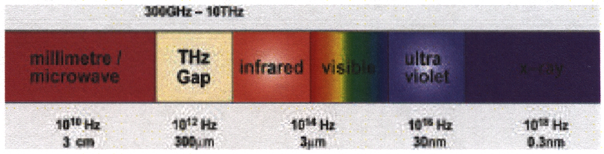

Figure 1: Electromagnetic wave spectrum

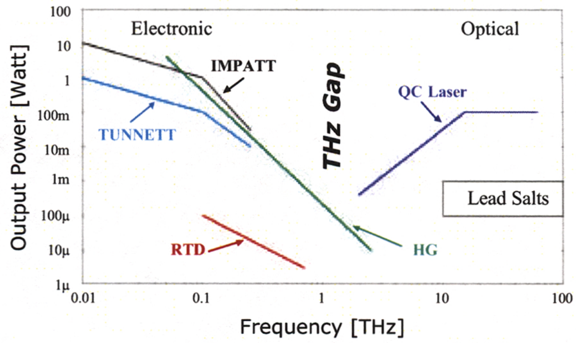

Figure 2: The THz gap [2]

Recently, it has been suggested [3] that the next generation of millimetre/terahertz wave devices should be the result of the combination of the virtues of vacuum tubes with solid-state microfabrication methods. Vacuum devices can be very efficient if a depressed collector is used, so much so that efficiencies greater than 40% are commonplace at microwave frequencies. In addition, the electron mobility is essentially infinite, whereas in a solid-state component, carrier mobility is a serious limitation and leads to device heating problems and reduced efficiency. On the other hand, solid-state fabrication methods lead to micron size accuracy, with good yields and the economy of mass production, so that it is now possible to construct the miniature vacuum electronic device components required for operation at very short wavelengths. This approach is already being applied to the development of terahertz range reflex klystrons at Leeds [4], and millimetre range klystrons at SLAC [5]. However, it is well known that in the microwave range at least, the travelling wave tube offers greater bandwidth and flexibility than the klystron, but

the construction of a helical structure in silicon would be highly complex if at all possible. However Bhattacharjee et al [6] have recently suggested that a folded waveguide travelling wave tube (FWTWT) is capable of being manufactured by microfabrication techniques in a straightforward way. A schematic diagram of such a FWTWT is shown in Figure 3. Its initial calculations indicate that a device 2.5cm long fabricated in silicon could achieve 10dB of gain at 500GHz when configured as an amplifier, with a saturated output of about 100mW. With the application of some positive feedback this amplifier could easily be converted into an oscillator that could possibly fill the Terahertz Gap.

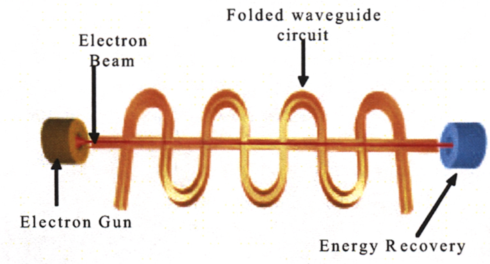

Figure 3: FWTWT THz System

As well as examining the feasibility of the FWTWT, the RF and Microwave research group (RFM) at Liverpool John Moores University intend to examine the possibility of miniaturising the FEL. The frequency of the output radiation from these devices is inversely proportional to the period of a undulator magnet and depends upon the voltage used to accelerate the electron beam [7-10]. Consequently, if operation in the terahertz gap is required, either the undulator period has to be reduced or the accelerating voltage increased or both. Reducing the period of the magnet is a difficult, labour intensive task and increasing the operating voltage makes the device unattractive for users. To overcome this problem, the RFM group proposes the use of an electrostatic undulator as shown in Figure 4. However, the interactive structure may be simpler but the overall system gain and efficiency are rather poor as shown in table 1 unless higher beam voltage >300kV used which is not the aim of our research to build a systems operating at only 10kV. Other structure is currently under investigations including the use of slow structure miniature Linac as shown in figure 5. The initial results operating at 135GHz looks very promising. This system lends itself more readily to miniaturisation than the magnetic undulator, which requires the adjustment of individual magnets, so that high frequency operation could be possible without resorting to very high accelerating voltages.

2 Modes of Operation

FWTWT operation can be described as follows. As an electron in the beam crosses one of the waveguide sections, it experiences either an accelerating or a decelerating force due to the transverse electric field of the TE10 mode of the radiation propagating along the guide. Provided the gap is not too wide so that each electron crosses in less than half a period of the radiation, a small amount of energy can be exchanged between an electron and the radiation. When this electron reaches the next gap, it can find itself in the same phase relative to the electromagnetic wave provided the distance travelled by the faster wave is adjusted properly relative to the distance travelled by the electron. In this way, energy can be repeatedly and cumulatively transferred between the electrons and the radiation in a similar way to a standard TWT. Electron bunches form as the accelerated electrons catch up with the decelerated ones, and if the accelerating voltage is adjusted properly, more electrons can be made to lose energy than gain, and as a result the radiation can be greatly amplified.

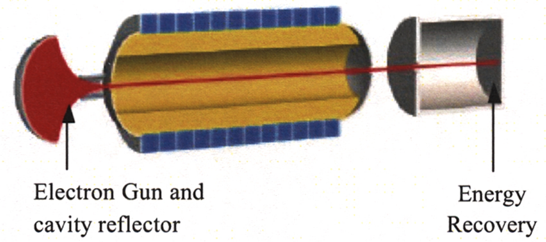

Figure 4: Electrostatic THz System

	2kV	20kV	60kV
λ_W / a	0.23	0.74	1.30
Ez (10kV/mm)	2.67×10^{-4} V/m	18.4 V/m	547 V/m
f_{op} (λ_W=1, Ie=200mA, N=100periods)	$\approx f_{co}$	1.04 f_{co}	1.12f_{co}
a	4.32mm	1.355mm	0.768mm
f_{op}	27.4 GHz	88 GHz	167 GHz
Gain	≈ 0	4×10^{-4}%	2×10^{-2}%

Table 1: Electrostatic undulator for the THz system

The folded waveguide itself has dimensions roughly 500 mm deep by 50 mm wide (across the gap) for operation at 500GHz, and could be manufactured in silicon by a number of techniques including LIGA, SU-8, and DRIE. The waveguide walls would have to be gold or copper plated to reduce attenuation; experimental results on waveguides micromachined in silicon at 100GHz show that the effects of surface roughness are minimal [11].

3 Design Considerations and Experimental Setup

The waveguide structure of the FWTWT is made by assembling a set of copper laminations containing a serpentine cut out, input and output waveguide tapers and an electron transport channel. This process is very similar to PCB manufacture. An etch resist mask is printed onto both sides of a sheet of metal and then the metal is spray etched to create the part.

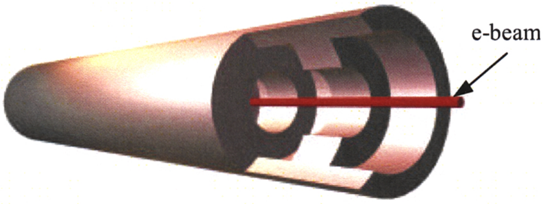

Figure 5: Miniature Linac

Figure 6 shows the complete stack of copper laminations sitting on one of the two 6mm thick aluminium side plates. Twenty-One stainless steel alignment screws have been made to ensure exact positioning of all the laminations. After the assembly is bolted tightly together, the ends of the laminations are cut off and made flush with the ends of the side plates. The laminations were made over length to be cut down in this way to ensure accurate alignment of the centre section, which would otherwise be a "floating" separate component as it is surrounded by the waveguide on both sides.

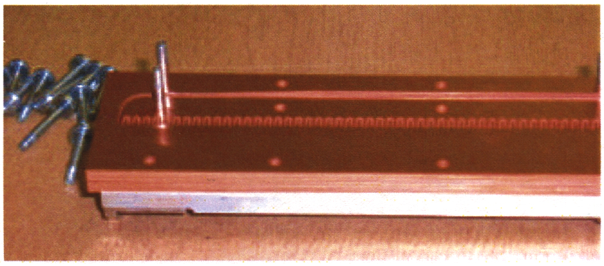

Figure 6: Stack of laminations mounted onto side plate.

The electron beam enters from the left hand side as viewed in this photograph. The channel the beam travels through cannot be seen in the photograph as it is buried down in the centre of the stack. After assembly, the FWTWT cavity is mounted on the front face of the electron gun chamber (figure 7). After the excess copper has been removed from the ends of the laminations, the entry and exit waveguides can be seen. The "input" waveguide is indicated by the closer positioning of the alignment screws. A "beam scraper" is positioned between the gun and the cavity assembly. This is simply a copper disc with a 0.5mm diameter hole in the centre. It performs two functions; firstly it protects the laminated structure from excess electron beam and secondly it acts as a spacer to lift the FWTWT structure above the level of the knife edge seal which has been put on the front face of the gun so that other equipment can be mounted using a CF flange. When in position, the FWTWT cavity is enclosed in a vacuum chamber (figure 8). The white parts in the photograph are just a curious effect caused by the camera flash where the aluminium has been cleaned after welding. The external waveguides will enter the chamber via two sliding connectors that allow them to butt up to the entry and exit ports on the cavity. This allows the waveguides to be removed should the solenoid magnet coil need to be taken off. In this way the waveguides can be structured without having to worry about their flanges passing through the centre of the solenoid. The complete system setup is shown in figure 9.

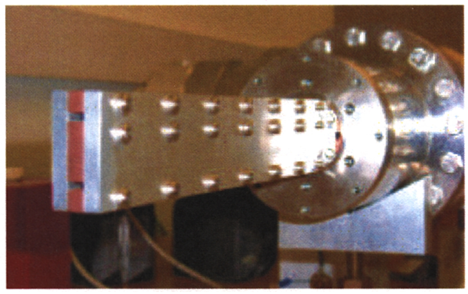

Figure 7: Assembled FWTWT cavity, mounted on electron gun housing.

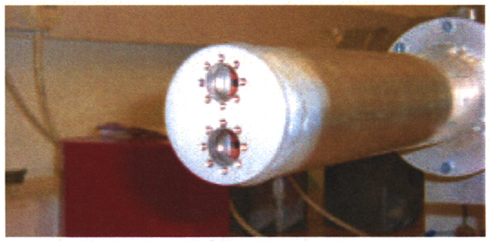

Figure 8: Vacuum chamber in position showing waveguide entry and exit points.

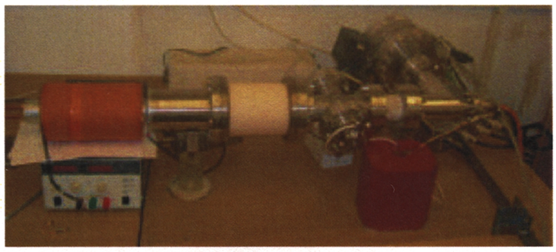

Figure 9: FWTWT complete system

4 Conclusions

This paper has briefly introduced various methods in constructing THz systems. The FWTWT has proven successfully and maximum frequency achieved based upon figure 6 set up was 96GHz, see figure 10. Higher frequencies can be obtained at much higher frequencies. However, the use of miniature Linac has proven to be the way forward. The system results are still under evaluation and analysis.

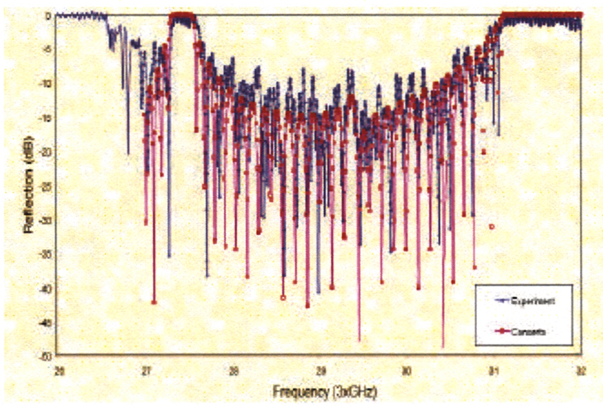

Figure 10: system experimental results

References

[1] Davies AG, Linfield, EH, and Pepper, M, eds: 2004, Discussion Meeting: Phil Trans Royal Soc, 362: 195-414

[2] Langdon, RM, et al., Military Applications of Terahertz Technology, 2004, EMRS DTC Conference Proceedings, A1

[3] Miles, RE, et al., 2000, Proc 8th International Conf in Terahartz Electronics Darmstadt

[4] Chamberlain, M, et al., 2001, IEEE PPPS-2001 Conference Record, IEEE Cat. No. 01CH37255, Las Vegas, NV, June 17-22

[5] Caryotakis, G, et al., 2000, Int. Vacuum Electronics Conference 2000 paper 1.5, Monterey, CA, 2-4 May

[6] Bhattacharjee, S, et al., 2004, IEEE Trans Plasma Science 32, 1002-14

[7] Dearden, G, Al-Shamma'a, AI, Quirk, EG, Stuart, RA and Lucas, J, 1994, Nucl. Instr. And Meth. In Phys. Res. A341, 80-84

[8] Al-Shamma'a, AI, Stuart, RA and Lucas,J, 1996, Nucl. Instr. And Meth. In Phys. Res. A375, 424-426

[9] Balfour, C, Stuart, RA and Al-Shamma'a, AI, 2004, Optics Communications 236, 403–410, 2004.

[10] Wright, CC, Stuart, RA, et al., 2005, Vacuum, 44, 4, 527-531

[11] Wright, JA, et al, 1995, Symposium Proceedings: Sixth International Symposium on Space Terahertz Technology, Pasadena, CA, 387-396