Compact Tuneable Terahertz Source

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Abstract

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.

Keywords: Folded waveguide travelling wave tube, microfabrication

Introduction

The region of the electromagnetic spectrum 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. 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.

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 [3]. 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.

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 did not appear to be feasible. Very recently though, Booske [6] has 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 a FWTWT is shown in Fig.1. 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.

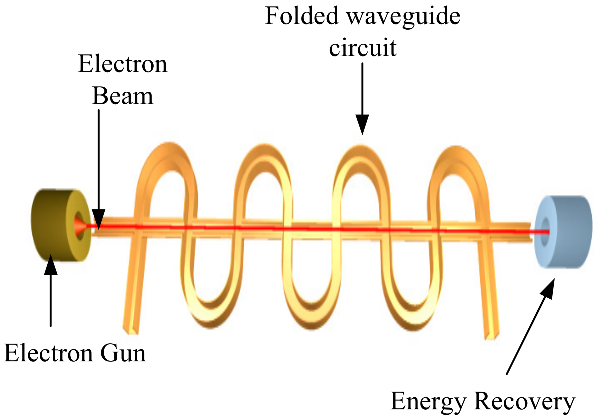

Figure 1: FWTWT THz System

As well as examining the feasibility of the FWTWT, we also intend to examine the possibility of miniaturising the free electron laser. The frequency of the output radiation from these devices is inversely proportional to the period of a so-called wiggler magnet and depends on the voltage used to accelerate the electron beam [7-10]. Consequently, if operation in the terahertz gap is required, either the wiggler period has to be reduced or the accelerating voltage increased or both. Reducing the period of the magnet is a difficult, labour intensive task, but increasing the operating voltage makes the device unattractive for users. To overcome this problem, we propose the use of a different type of wiggler, the *electrostatic* wiggler as shown in Fig.2. This system lends itself more readily to miniaturisation than the magnetic wiggler, which requires the adjustment of individual magnets, so that high frequency operation could be possible without resorting to very high accelerating voltages.

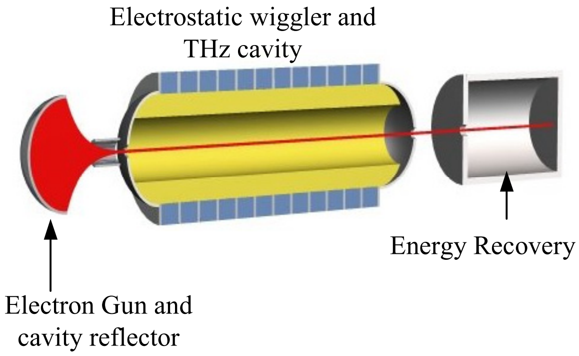

Figure 2: Electrostatic THz System

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 TE_{10} 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.

The folded waveguide itself has dimensions roughly 500 μm deep by 50 μm 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 device would probably have to be manufactured in two halves to allow for the electron beam tunnels to be constructed as a slot in each half. 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].

The electrostatic wiggler free electron laser works in a very similar fashion, but now the static voltages on the electrodes imposes a spatial modulation of the electron velocity. Technically, spatial harmonics can be said to have been imposed on the electron beam, rather than on the electromagnetic wave as in the case of the FWTWT, in order to achieve a gain condition. If operation were restricted to 60kV (a level not too difficult to achieve with standard laboratory power supplies) the spacing of the washer shaped electrodes of the wiggler would need to be about 150 μm for operation at 500GHz. The structure then could be built up from laser cut metal and dielectric foils.

Future work

Before any of the practical constructional problems of miniaturisation can be considered properly, an appropriate design procedure for each device has to be derived. The most important first step is a calculation of the power gain to be expected in each case as a function of the dimensions of the device, the number of folds/wiggles, the accelerating voltage and the beam current. At present, there is no simple analytical model for the FWTWT that includes the effects of space charge repulsion, which is well known to be very important in the operation of microwave TWTs. Numerical software does exist for the design of TWTs, but is expensive, requires a large amount of computer run time, and does not provide the physical insight necessary to allow a device to be optimised rapidly. The diameter of the electron beam tunnels for the FWTWT is also an important design parameter. If it is too large, the radiation in the waveguide will leak from one section to its neighbouring sections, thereby reducing the gain. If the tunnel diameter is too small, this will reduce the electron beam current that can be transported without excessive interception, which will again reduce the gain. The accuracy of the positioning of these tunnels is also an important factor, since, if they are poorly placed, stop bands in the transmission of the radiation through the waveguide occur which interferes with the broadband operation of the device.

The radiation transmission characteristics of the electrostatic wiggler structure will also be investigated. Since it is a periodic structure, stop and pass bands are to be expected. The dimensions of the device will have to be determined so that these stop bands do not interfere with the correct operation of the device.

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Acknowledgements

The work reported in this paper was funded by the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence and run by a consortium of SELEX Sensors and Airborne Systems, Thales Defence, Roke Manor Research and Filtronic.