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A COMPARISON OF THE PERFORMANCE OF MILLIMETRE-WAVE SEMICONDUCTOR OSCILLATOR DEVICES AND CIRCUITS.

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ABSTRACT

A comparison of the commonly used millimetre-wave semiconductor devices is made; the Si IMPATT, GaAs TED and InP TED. The comparison is made on the basis of the primary characteristics of output power and efficiency as well as the secondary effects of amplitude and frequency stability, including a.m. and f.m. noise. A review of the waveguide circuit techniques employed with these devices is presented, emphasising the size limitation and susceptibility to severe environmental loadings. A miniature microstrip oscillator structure employing an InP TED as the active element is described. This source has produced 32 mW at 81 GHz in microstrip and highlights the potential suitability for rugged, integrated transmitter/receiver subsystems operating at millimetre wave frequencies.

INTRODUCTION

A comparison has been made of the performance characteristics of the GaAs and InP transferred electron devices (TEDs) and the Si IMPATT device at millimetre-wave frequencies (75-110 GHz). Historically applications for TEDs have been for low noise, low power local oscillator requirements whereas the avalanche device has been almost exclusively used for transmitter type applications because of its higher output power capability. However, recent measurements at these laboratories have shown that the IMPATT device can be used in a lower power mode and made to exhibit improved noise characteristics making it potentially suitable for some local oscillator applications, especially where high mixer drive levels are required. This paper attempts to outline the considerations that must be made before a device can be selected for a particular system. The r.f. performance obtained using conventional waveguide circuit techniques is reported and includes noise suppression by cavity stabilisation and temperature compensation. However, the limitations of waveguide circuits in terms of size, weight and manufacturability become significant at millimetre wave frequencies and future trends are toward rugged, miniature oscillators capable of operating under severe environmental conditions. The first results obtained from the InP TED used in a quartz microstrip circuit are presented and indicate that there may be some advantage in employing this device in an integrated system.

DEVICE PERFORMANCE

With regard to the primary characteristic of output power capability, the Si double drift IMPATT device is superior by far to either TED, powers in excess of 200 mW at 94 GHz being readily achievable[1] using gold heatsinks with conversion efficiencies up to 10%. With the use of diamond heatsink technology a CW output power of 1 watt (77.7 GHz, 8.1%) has been demonstrated[2]. The TEDs offer somewhat less, with the conventional ohmic contact InP device routinely producing 60 mW at 80 GHz with 2.5% conversion efficiency. The highest reported power level at this frequency is 120 mW (3%)[3]. The mode of operation of the InP TED is one of fundamental oscillation whereas power can only be obtained from the GaAs TED by using it in the harmonic extraction mode[4]. The conversion efficiencies are consequently lower and power levels are normally in the range 30 mW (80 GHz) to 20 mW (94 GHz). A summary of the typical output powers obtained from the three device structures is shown in Figure 1, assuming a similar processing technology (gold heatsinking) and operation at temperatures likely to ensure reasonable reliability.

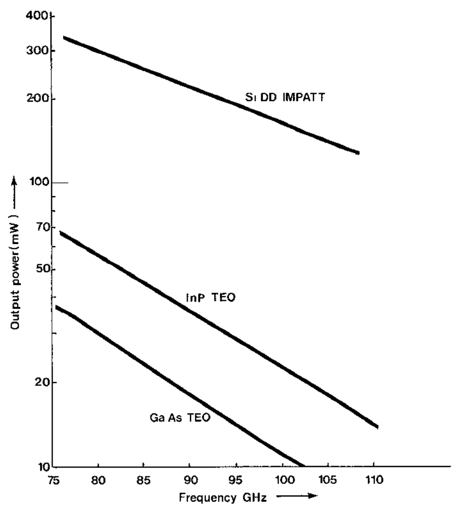

FIG.1. TYPICAL OUTPUT POWER CAPABILITIES OF (a) Si DD IMPATT, (b) InP TEO, (c) GaAs TEO AT W-BAND (75-110 GHz)

Second order parameters are usually very important to system designers. For example, the temperature sensitivity of output power produced by the InP TED, typically -0.01 dB/°C, is notably less than that of the GaAs device, -0.02 dB/°C. This is primarily because the fundamental material parameters affecting device conversion efficiency are less temperature sensitive in InP. But for radar system design, where most solid state devices find application, noise performance is usually the most important. Measurements of both f.m. and a.m. noise have been made on all three structures. The f.m. noise measurements were made using a delay-line discriminator technique[5], the system sensitivity being set essentially by the incident power into the noise bench. This is usually fixed at 10 mW and corresponds to a measurement limit of -45 dBc/Hz SSB at 1 KHz offset falling at approximately 30 dB/decade. The a.m. noise measurements were made using a simple direct detection method and, although less sensitive than other more sophisticated techniques, yield a system detection limit of around -170 dBc/Hz SSB at 10 MHz offset. Results have presently shown the GaAs TED to be superior in terms of f.m. performance to the InP TED by typically 10-15 dBc/Hz, both exhibiting the normal 1/f or flicker noise behaviour, whereas the a.m. performance appears very similar being close to the measurement limit of the technique employed (Figure 2). However, it must be noted that the harmonic mode of operation of the GaAs device leads to an anomolously high value of external Q as well as lower conversion efficiency. Comparisons made at 34 GHz on fundamental mode oscillators show the f.m. noise performance of GaAs and InP TEDs to be similar, i.e. it is likely that the noise measure of the two devices are similar. Decoupling of the InP TED by a small amount does result in a significant improvement in f.m. noise.

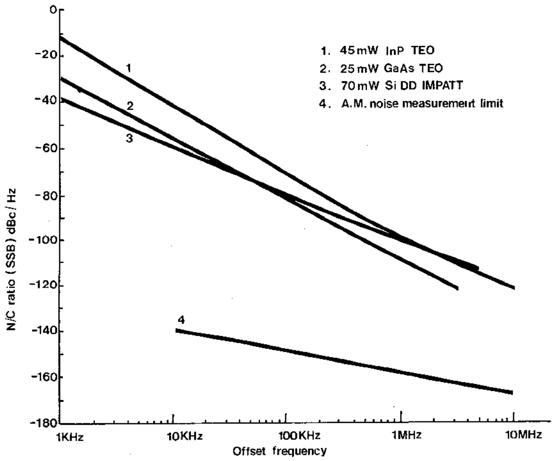

FIG.2. NOISE MEASUREMENTS AT 80GHz

The most surprising result that has emerged from the f.m. noise measurements has been the performance of the Si IMPATT. Operating close to maximum output power the noise performance is, as is expected, somewhat poorer than the TED. However, at lower drive levels, but still with output power and efficiency superior to TEDs the close to carrier f.m. noise performance is notably better, at least to offset frequencies of 50 KHz. Figure 2 shows the detailed behaviour of typical devices. The Si IMPATT is also often rejected for some applications on the grounds of high a.m. noise, but it has also been shown that in this 'detuned' mode the a.m. noise of the avalanche device is similar to, if not better than, that of the TEDs. Measurements made on all three devices are close to the present system limit shown at Figure 2. The reasons for this low noise behaviour observed in Si IMPATT devices is discussed fully at reference 6 but, in brief, there are two significant points to note. Firstly, this 'detuned' mode is only achieved when the circuit conditions are carefully set up. Secondly, and more important, the operating current density in the device is set such that the output power is less than approximately 75% of the maximum achievable power. IMPATT device performance is normally reported on the basis of power output and efficiency, usually quoted near burn-out conditions where the spectrum is poor, however it can now be seen that the possibility exists for the use of lower power 'detuned' IMPATTs for low noise applications. Of course, other considerations must be taken into account, including the type of power supplies available, manufacturability, yield etc.

CIRCUIT TECHNIQUES

Optimum performance is achieved from all the above device structures by employing metallic waveguide circuits, usually using the resonant radial-cap mode. These cavities and their fittings are broadly speaking based on lower frequency circuits. Because the dimensions are so much smaller at millimetric wave frequencies, the manufacture of these waveguide circuits is difficult with extremely precise machining tolerances being required. The completed oscillator is therefore usually expensive as well as being relatively large and heavy. They are also particularly susceptible to severe environmental loadings such as high shock levels in the plane of the radial cap. The maximum tolerable level for this is approximately 500-1000g for short durations without introducing supporting structures that may compromise performance or complexity.

Despite this, conventional circuit techniques have been scaled from lower frequencies and successfully applied to millimetre-waves. For example, cavity stabilised oscillators have been manufactured employing both transmission and reflection mode resonators. The resonators used are TE_{011} cylindrical cavities with sputtered silver internal surface layers to improve the unloaded Q value. Even having taken this and other precautions, measured values of Q_0 are approximately 2,000, only 30% of the theoretical values indicating once more the difficulty of manufacturing millimetre-wave components. Suppression of the f.m. noise on InP TEDs by 20-25 dB has been achieved using cavity stabilisation. The circuits have been used to demonstrate very low noise, stable oscillator structures delivering 20 mW fixed frequency (transmission mode stabilisation) and 34 mW mechanically tunable over 1 GHz (reflection mode stabilisation). Figure 3 shows a photograph of the transmission stabilised source.

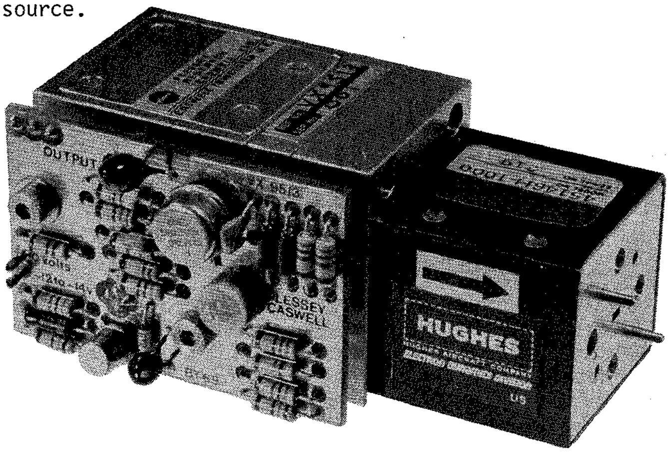

FIG.3 TRANSMISSION CAVITY STABILISED WAVEGUIDE OSCILLATOR

A regulator p.c.b. is fitted to the oscillator which not only provides d.c. regulation but is also used to compensate for drift of the oscillator frequency with temperature, normally -10 MHz/°C. Bias pushing is employed to reduce this figure to -1.7 MHz/°C to accurately track the frequency of the stabilising resonator. The associated f.m. noise performance of both cavity stabilised oscillators is shown at Figure 4.

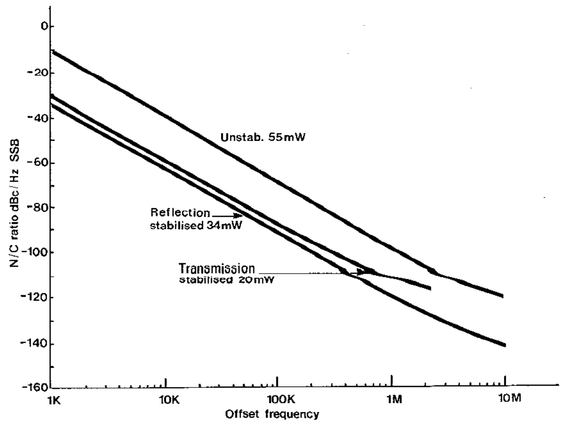

FIG.4. FM NOISE FOR REFLECTION CAVITY AND TRANSMISSION CAVITY STABILISED 80 GHz InP TEO's

However, future trends are toward rugged, miniature oscillator structures with a view to high volume, low cost production. The approach has been to investigate both 0.005" microstrip and 0.028" x 0.056" image guide fabricated in Z-cut quartz with the aim of incorporating the active device directly into the solid medium rather than employing an 'off-substrate' metallic resonator. The first circuits to be made have employed the InP TED as the active element in conjunction with a simple two-section matching network on microstrip. A schematic of the circuit is shown at Figure 5.

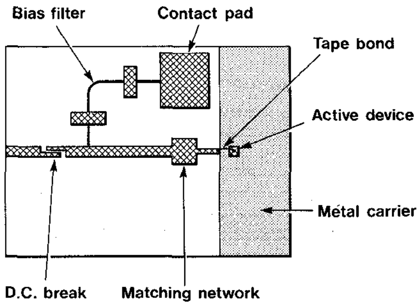

FIG. 5 SCHEMATIC OF MICROSTRIP OSCILLATOR CIRCUIT

The circuit was incorporated in a test assembly and fitted with a waveguide/microstrip transition for assessment purposes. The design of this transition was not fully optimised and in conjunction with the d.c. break amounted to ∿3 dB loss. The highest power recorded at the waveguide output port was 16 mW which corresponds to over 30 mW at the microstrip oscillator, approximately 75% of the power demonstrated by similar devices in a fully optimised waveguide cavity. The operating frequencies were in the range 81-83 GHz very close to the design aim of 80 GHz. An assessment of the oscillator stability has indicated this to be very similar to equivalent waveguide oscillators and in fact detailed f.m. noise measurements have shown this to be the case. Figure 6 shows a photograph of a typical spectrum analyser trace.

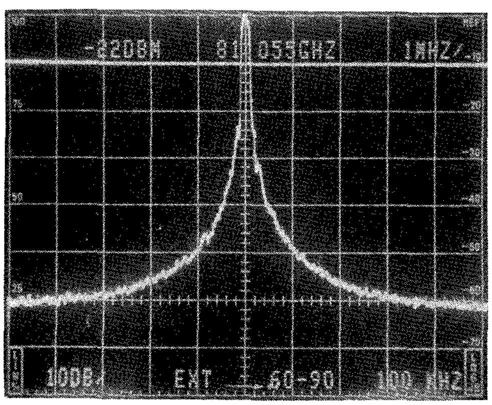

FIG. 6 R.F. SPECTRUM OF MICROSTRIP OSCILLATOR

The high degree of stability and circuit efficiency achieved is a consequence of the relatively high device impedance of the InP TED, making it more straightforward to extract power using simple circuit techniques. Other workers in this field using Si IMPATT devices for example have been less successful, only demonstrating a small fraction of the device capability[7]. This may be because the real part of the IMPATT device admittance is typically only a few ohms and it is difficult to realise an efficient matching network for such a device. The GaAs TED operating in the harmonic mode relies largely upon carefully controlled circuit elements very close to the device terminals, such as package parasitics, and would be more difficult to employ in microstrip. For these reasons, the authors consider the fundamental mode InP TED well suited for use in fully integrated microstrip structures.

CONCLUSIONS

This paper highlights the difficulty in selecting the 'right device' for use in millimetre-wave radar applications. The choice is no longer simply low noise TEDs for local oscillators and high power IMPATTs for transmitters. The system designer must take many other factors into consideration; output power and efficiency; f.m. and a.m. noise; the offset frequency at which noise is important; ease of manufacture; size, weight and cost; suitability for integration. The three semiconductor devices most commonly used for power generation at millimetre-wave frequencies have been described and the suitability of each with regard to a particular requirement must be carefully considered.

ACKNOWLEDGEMENTS

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