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THz Radiation using Compact Folded Waveguide TWT Oscillators

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Abstract — **Microfabricated folded waveguide traveling wave tubes are a promising solution to the generation of compact, wideband, high power terahertz radiation. We present feasibility studies of an oscillator concept using an amplifier with recirculated feedback. Simulations of a 560 GHz oscillator and experimental verification of the principle at 50 GHz are presented. Observation and measurements are reported on the generation of stable single frequency oscillation states. On varying the feedback level, the oscillation changes from a single frequency state at threshold to multifrequency spectra in overdriven state. Investigations on dynamics of the regenerative TWT oscillator will be presented. Additionally, preliminary results of experiments to fabricate 100-400 GHz folded waveguide TWT circuits will be reported.**

I. INTRODUCTION

The terahertz region of the electromagnetic spectrum (~ 300 – 3000 GHz in frequency or ~ 0.1 – 1.0 mm free space wavelength) has enormous potential for high-data-rate communications, advanced electronics materials spectroscopy, space research, medicine, biology, surveillance, and remote sensing. However, this region of the spectrum still remains one of the most unexplored. Using carrier frequencies above 300 GHz, oscillator and amplifier sources with ~10% fractional bandwidths would enable very high data rate (> 10 Gbits/s) wireless communications with high security protection. The shorter wavelengths at these frequencies allow the use of smaller and lighter components, which is important in military and space-borne applications. In addition, the atmospheric attenuation of millimeter and submillimeter waves is relatively low compared with infrared and optical wavelengths [1]. Adequate power sources in the THz regime would also enable imaging of biological tissue, where specific absorption rates (SARs) are large, and hence require more power.

However the critical roadblock to full exploitation of the THz band is the lack of compact, powerful (1-1000 mW) coherent radiation sources that are efficient (> 1%), frequency agile (instantaneous bandwidth > 1%), reliable and comparatively inexpensive [2].

Amongst the available candidate sources, for a variety of reasons [3-5] we have chosen folded waveguide traveling wave tubes to address the need and issues of THz-regime sources. The microfabricated folded waveguide traveling wave tubes are a blending of available technologies in conventional vacuum and solid state electronics.

II. AMPLIFIER AND OSCILLATOR DESIGN AT 560 GHZ

The methodology and other details on an illustrative amplifier and oscillator design at 560 GHz such as dispersion, interaction impedance, attenuation, small signal gain and drive curves have been already presented earlier [3-5]. In this section we present results on simulation of feedback oscillations.

A. *Simulation of feedback oscillations*

The electromagnetic simulation code MAFIA was used for the investigation of frequency evolution with variable feedback. The simulations were carried out for oscillator circuit parameters of beam current 0.5 mA, beam voltage 10.9 kV, axial magnetic flux density 0.67 T and beam to tunnel radius of 0.5. Extensive computation times necessitated compromises in the simulations : (1) a small length of the circuit was considered which provided a forward gain of approximately 9.75 dB (2) duration of simulation time was limited by allowing the oscillator to run approximately nine full round-trip transits of the electromagnetic energy. The loss was simulated by filling a portion of the rectangular waveguide in the recirculation leg with a lossy dielectric material. The length of the dielectric was varied to achieve four cases:

total attenuation in the return path of (a) 0 dB (b) –8.75 dB (c) –9.75 dB, and (d) –10.75 dB.

The time varying electric fields were monitored at several locations within the simulated geometry. Discrete Fourier transforms (DFT) were performed on them to investigate how the excitation frequency evolved with time.

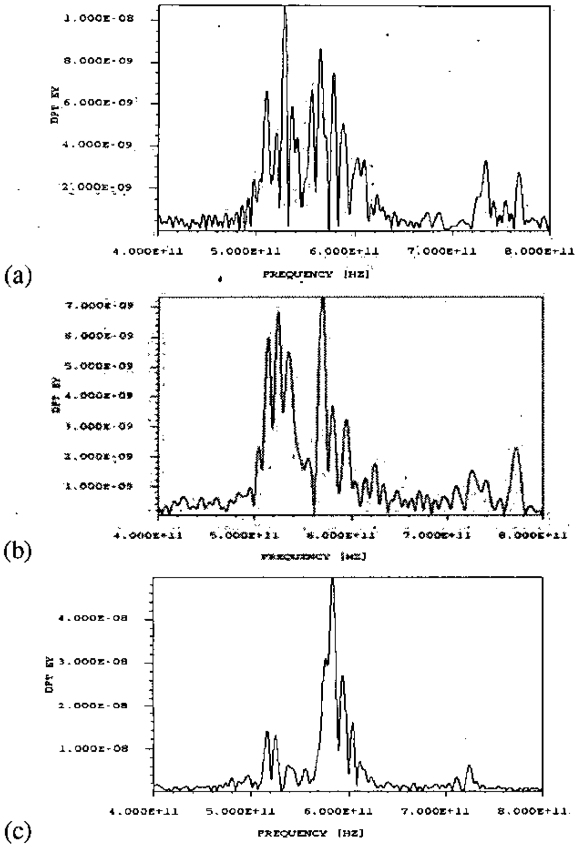

Fig. 1. Evolution of oscillations for the 560 GHz oscillator. (a) -9.75 dB loss. (b) - 8.75 dB loss and (c) 0 dB loss.

Fig 1 (a) illustrates an overdriven case of large feedback with 0 dB return loss. The spectrum does not lock into any single frequency, and a broad, multifrequency oscillation spectrum over the 528 – 580 GHz regime is observed. When the return path loss is increased to approximately –8.75 dB, the oscillator appears to self-selecting two preferred frequency states around 520 and 580 GHz (Fig. 1 (b)). When the loss is further increased to –9.75 dB, oscillation in a single frequency state at 580 GHz is seen (Fig. 1 (c)). Finally, when the loss is increased to 10.75 dB, there is no spontaneous signal growth as the loss in the return path exceeds the forward gain.

B. Time frequency analysis

When the (time-integrated) DFT spectrum shows multiple frequencies, it is of interest to know whether this represents unstable hopping between the frequencies or simultaneous generation of multiple frequencies. DFTs do not provide the answer to this question, particularly when the spectral evolution occurs on a relatively fast time scale.

As the time window is narrowed, one loses resolution and the information gets distorted. William's [6] binomial time-frequency-distribution program was utilized earlier for the time-frequency-analysis of modulation in high-power microwave sources [7]. In this study it was used to analyze data from the MAFIA simulations (section II A) for the –8.75 dB and –9.75 dB cases of return loss. Results indicate that for the case of intermediate feedback (-8.75 dB) the oscillator is hopping between two preferred oscillation states at ~ 520 GHz and 580 GHz. In contrast at near critical feedback (-9.75 dB) the oscillator settles down into one preferred frequency at ~ 580 GHz.

III. EXPERIMENTAL SET-UP AND METHODS

To investigate the physics of the regenerative oscillator, a scaled experiment at 50 GHz was carried out. The 50 GHz FWG-TWT was previously developed and studied as a high-power millimeter-wave amplifier [8].

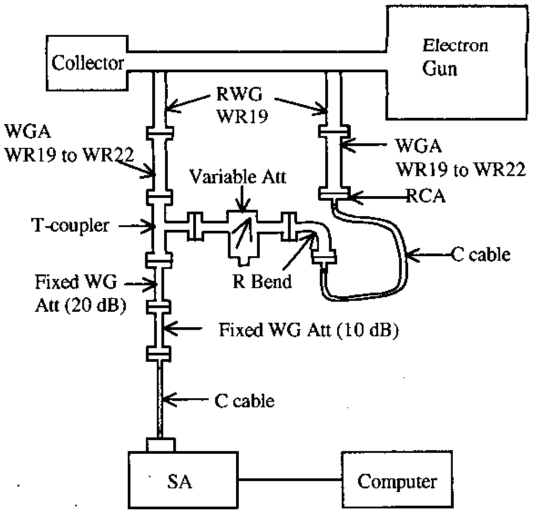

Fig. 2 A schematic of the experimental system for the 50 GHz FWG-TWT oscillator.WGA: Waveguide adapter, RCA: Rectangular to Coaxial adapter, Att: Attenuator, C: Coaxial, R: Rectangular, SA: Spectral analyzer.

Figure 2 shows a schematic of the experimental assembly. The amplifier has been converted into an oscillator by using an external feedback loop which consists of waveguide components, a variable attenuator to vary the level of output power fed back to the input, and a T-coupler for coupling a fraction of the output power into a spectrum analyzer for measurement purposes. The beam voltage and current are 20-21 kV and 60-100 mA respectively. Measurements were made in the pulsed mode with 200 μs long pulses with a repetition rate of 5 pulses/s. The generated frequency spectrum was observed using a HP 8565 E (30 Hz – 50 GHz) gated spectrum analyzer.

IV. EXPERIMENTAL RESULTS

A. Spectral evolution

By varying the attenuation in the feedback leg using the variable attenuator, we observed the self-selected oscillation frequencies at different feedback power levels. The total attenuation in the feedback leg can be varied between -3 to -30 dB over the 40 – 50 GHz range. This includes the losses by all rf components and cables.

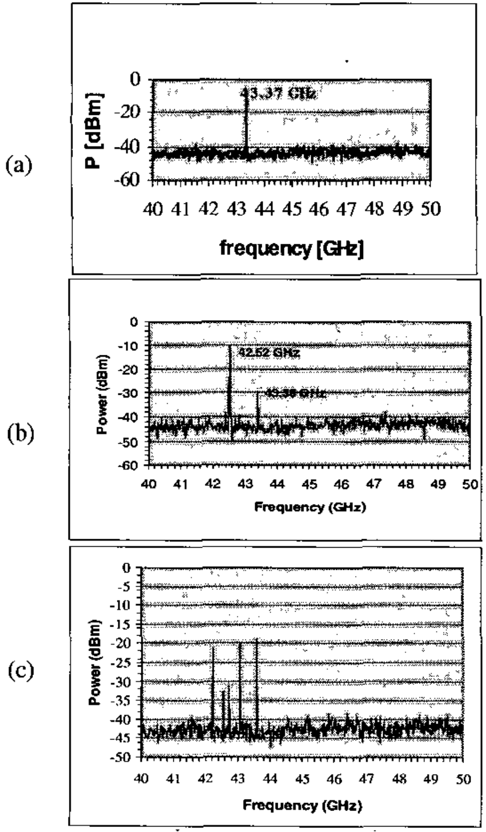

Fig. 3 Spectral evolution with feedback attenuation.

At full attenuation no oscillations are observed. The critical feedback threshold appears at ~ -26 dB where stable single frequency oscillations at 43.4 GHz are observed (Fig. 3 (a)). Fig. 3 (b) shows a case of intermediate feedback at –8.25 dB. Here two dominant frequencies are observed. Finally, at even lower levels of attenuation, no clear tendency is observed and the spectrum consists of many frequency components. These results agree very well with the simulation results of section II A.

B. Frequency response of feedback leg and amplifier gain

The frequency response of the feedback circuit was measured using a Hewlett Packard 83650 L swept cw generator (10 MHz – 50 GHz). The general conclusion was that the feedback leg's attenuation was only weakly dependent on frequency. This measurement revealed that the feedback circuit's attenuation does not determine the oscillation frequency.

Next, the small signal gain of the FWG-TWT amplifier was measured. Figure 4 shows the result on two different runs of the experiment represented by dark triangles and squares. On the same plot shown by a line is the result of simulation (using the CHRISTINE code [9]) for a beam voltage of 20.75 kV and a beam current of 60 mA. The maximum gain is about 27 dB at ~ 43 GHz. Gain occurs between 42-44 GHz, precisely where the self-selected oscillations were observed.

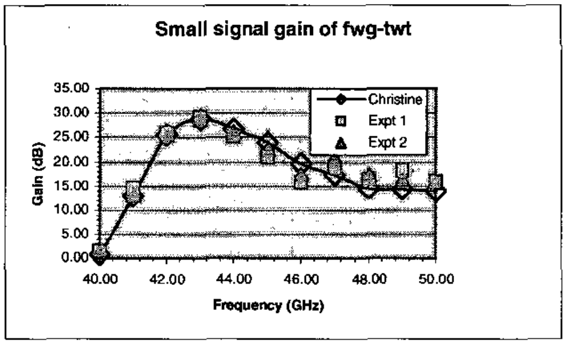

Fig. 4 Small signal gain of the 50 GHz FWG-TWT amplifier.

Finally, experiments were conducted varying the total phase shift in the feedback leg. The oscillation frequency can be switched by changing the feedback phase. This effect is being studied further.

V. FABRICATION EXPERIMENTS AT 400 GHZ

Two main approaches of fabrication are under investigation. One uses LIGA and the other uses Deep Reactive Ion Etching (DRIE). The LIGA process produces electroplated copper circuits. In the DRIE process silicon is etched and coated with copper. Both techniques involve forming serpentine waveguide circuits as two halves and bonding the halves to form complete waveguide circuits. We have successfully developed LIGA circuits and demonstrated the feasibility of fabricating DRIE circuits. The approximate spatial period of a 400 GHz serpentine circuit is about 100 - 200 μm. We are now investigating micromolding methods for circuit replication.

IV. SUMMARY

The simulations and experiments have both demonstrated the capability of generating stable single frequency oscillations using a recirculated feedback oscillator approach. Variation of the amount of recirculated power provides controllability over the generated oscillations. The results have clarified fundamental questions on oscillation thresholds, steady states and on the evolution of self-selected oscillation frequencies. The data indicate that frequencies with the highest gain are self-selected. Adjusting the phase of the feedback leg provides limited frequency tenability. This has an impact on amplifier design for future experiments. The time frequency analysis provides further insights on frequency selection. At an intermediate feedback, there is a clear indication of frequency hopping between two possible higher and lower frequency states. The observation of multi-frequency oscillation states on overdriving the amplifier has important implications. Chaos identification and control in a TWT is a topic of current interest. These areas definitely deserve further investigation.

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