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THz radiation using high power, microfabricated, wideband TWTs

C. L. Kory[1], J. H. Booske, W.-J. Lee, S. Gallagher, D. W. van der Weide, S. Limbach, and S. Bhattacharjee

[1]Analex Corp./NASA Glenn Research Center, 21000 Brookpark Road, MS 54-5, Cleveland, Ohio

University of Wisconsin-Madison, Electrical and Computer Engineering Dep't, 1415 Engineering Drive, Madison, WI 53706

***Abstract* — Microfabricated, miniature, folded waveguide traveling wave tube (FWG-TWT) devices are potential compact sources of wideband (~ 20 % instantaneous bandwidth), high power (0.01 – 1 W) THz radiation. We present theoretical analyses and numerical simulations indicating that a 560 GHz, 56 mW, 1% (intrinsic) efficiency oscillator is realistically achievable, and amplifiers with gains between 10 and 30 dB are feasible with circuit lengths of a few centimeters. We also discuss a scale-model experiment at 50 GHz to investigate an oscillator concept using a recirculated power feedback approach, and a 400 GHz proof-of-concept amplifier.**

I. INTRODUCTION

The terahertz (THz) 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 electronic materials spectroscopy, space research, medicine, biology, surveillance, and remote sensing. 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. 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.

Unfortunately, a critical roadblock to full exploitation of the THz band is lack of coherent radiation sources that are powerful (0.01 – 10.0 W CW), efficient (≥ 1 %), frequency agile (instantaneous fractional bandwidths > 1 %), reliable, compact, and relatively inexpensive. Solid-state sources satisfy the low voltage requirement, but are many orders of magnitude below the *combined* requirements for power, efficiency, and bandwidth. Typical fast-wave vacuum electron devices (VEDs) in this regime, such as gyrotrons and free electron lasers, tend to be large, expensive, high voltage and very high power, unsuitable for most of the applications cited above. Figure 1 shows the approximate CW power capabilities in different frequency bands of compact coherent radiation sources that are currently available based on reports in published literature. Both the IMPATT diodes and the BWO sources have fairly narrow instantaneous bandwidths and very low efficiencies (< 0.01%).

To address the need for compact THz radiation sources (amplifiers and oscillators), we are investigating the prospects for microfabricated vacuum electron devices, or "micro-VEDs". Micro-VED technologies are already being applied to the development of millimeter-wave klystrons at Stanford Linear Accelerator Center [1], THz regime reflex klystrons at the University of Leeds [2] and NASA's Jet Propulsion Laboratory [3], and transit time oscillators at the University of Michigan [4]. In contrast, we are designing, simulating and fabricating THz regime folded-waveguide traveling-wave tubes (FWG-TWTs) [5].

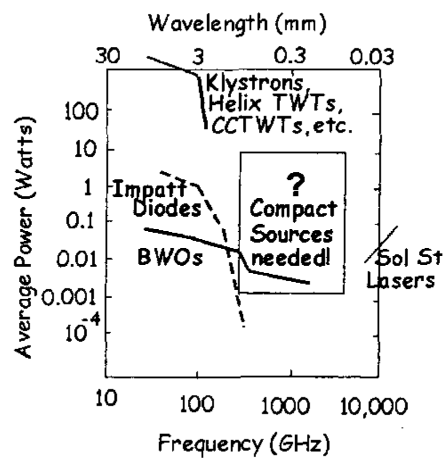

Fig. 1. Compact coherent radiation source capabilities

II. CONCEPTUAL DESIGNS OF FWG-TWT MICRO-VED AMPLIFIERS AND OSCILLATORS

The FWG-TWT has several features that make it attractive for THz-regime micro-VED applications: it employs a relatively simple circuit to design and fabricate, it is amenable to micromachining, and it has been demonstrated to be capable of forward-wave amplification with appreciable power and bandwidth [6]. A three-

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dimensional (3D) view of the FWG slow-wave circuit is shown in Fig. 2. We are pursuing computational and experimental studies of micro-VED FWG-TWT amplifiers and oscillators to establish their feasibility for sources in the 0.2 – 1.0 THz frequency regime.

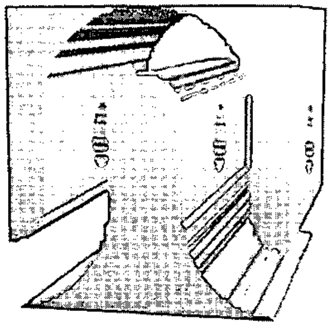

Fig. 2. Three-dimensional cutaway view of one bend in a simulated folded waveguide circuit using MAFIA.

Designing FWG-TWTs to meet gain, bandwidth, power, and operating frequency band specifications is nontrivial due to the dispersive properties of the circuit, the effect of beam space charge on the gain and operating bandwidth, and the effect of ohmic wall losses, which are significant at THz regime frequencies. To realize an efficient and reliable design approach, we have coordinated the use of several recently developed computational tools: OptSyn, MAFIA, HFSS, TWA3, and CHRISTINE1D. First pass selection of nominal circuit and electron beam parameters is obtained with the assistance of "OptSyn", a proprietary design methodology developed by Northrop Grumman Corporation. Slow-wave circuit cold-test data is obtained using the 3D electromagnetic codes MAFIA [7] and HFSS [8], and used as input into the TWT interaction codes, TWA3 [9] and CHRISTINE1D [10] to determine gain and power transfer characteristics. In addition, the time-domain, particle-in-cell (PIC) simulation feature of MAFIA has allowed us to conduct interaction simulations, as well as qualitative examinations of transient startup phenomena in THz regime oscillators that utilize a FWG-TWT as the active gain part of the device.

Using these computational models, we have developed realistically achievable designs for a 560 GHz oscillator and a 400 GHz amplifier as described below.

A. 56 mW, 560 GHz, FWG-TWT Oscillator

Several options for feedback were considered in investigations for the feasibility of THz-regime oscillators based on the FWG-TWT. Simulations show that reflecting the forward power backwards along the FWG circuit (a "Fabry-Perot" approach) is impractical due to the high ohmic losses suffered by the reflected wave at THz frequencies. However, recirculating a fraction of the forward wave back to the input of the circuit through a separate, straight, return leg is a viable option (Fig. 3). Additional reductions of loss on the recirculated power are possible by up-tapering the small lateral dimension of the rectangular waveguide, as suggested in Fig. 3.

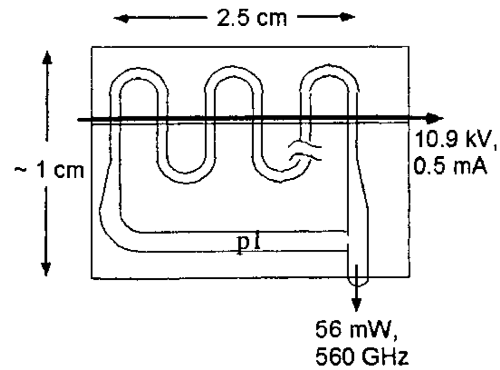

Fig. 3. Conceptual compact FWG-TWT oscillator design for producing ~ 56 mW CW between 500 and 600 GHz.

Applying the suite of computational models to this recirculated-feedback oscillator configuration has produced the self-consistent conceptual design for a 560 GHz FWG-TWT. Shown in Fig. 4 are the results of a calculation of the small-signal gain of a short, 6.6 mm long section of the circuit, assuming a 10.9 kV, 0.5 mA electron beam. The gain was calculated with several different computational models and compared for consistency.

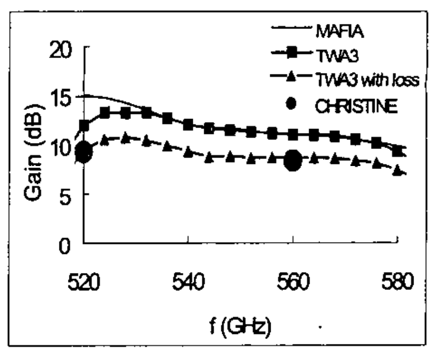

Fig. 4. Small signal single pass gain for a 6.6 mm long FWG-TWT designed to operate at ~ 560 GHz. The simulation assumes a 10.9 kV, 0.5 mA electron beam.

The MAFIA simulations were done for a lossless circuit only, but the agreement with the parametric code TWA3 is excellent. Furthermore, both TWA3 and CHRISTINE agree in predicting approximately 10 dB gain between 520 and 580 GHz (a 10% fractional instantaneous bandwidth) when wall losses are included (assumes an effective wall conductivity of $\sigma \sim 4 \times 10^7$ S/m).

An analysis of a 2.5 cm long version of this FWG-TWT with recirculated feedback (Fig. 3) indicates the interesting possibility of a ~ 56 mW steady state oscillator at ~ 560 GHz. This represents an intrinsic efficiency of 1%, which is substantially higher than either solid state or BWO sources at this frequency. It should be noted that increased device efficiency and decreased waste heat dissipation at the beam collector are to be expected from the addition of a depressed voltage collector.

The 3D PIC solver of MAFIA was used to investigate spontaneous RF excitation of this oscillator configuration. A lossless structure was assumed and the geometry simplified slightly (e.g., no waveguide up-taper on the return leg) to reduce computational time. Even so, this is a substantial computational modeling problem, requiring many hours of simulation. Fig. 5 shows the results of monitoring the electric field at point "p_I" in Fig. 3 during the transient onset of oscillation. The simulated interval of Fig. 5 represents about four round-trip transit times of the entire oscillator circuit. A discrete Fourier transform of the waveform in Fig. 5 indicates that the emission covers a 520-580 GHz spectral band, the range over which the FWG-TWT has positive gain (see Fig. 4). We now seek to determine whether this oscillator configuration will (without further modification) lock onto a single dominant frequency or will generate a noisy, broadband steady state signal.

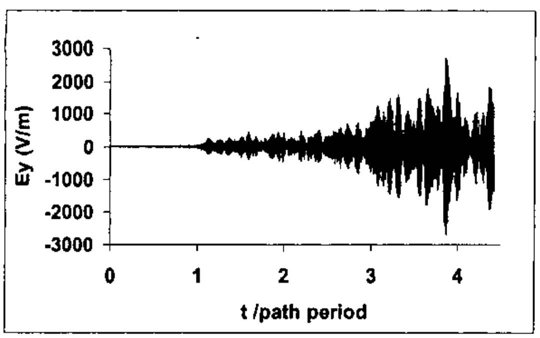

Fig. 5. Time-domain waveform of the transient onset of oscillation in the FWG-TWT oscillator of Fig. 3. Shown is the transverse component of electric field sampled in the recirculated feedback waveguide leg at point "p1" shown in Fig. 3.

B. 174 mW, 400 GHz, FWG-TWT Amplifier

The computational codes were also used to design a 174 mW, 400 GHz FWG-TWT amplifier assuming a 12 kV, 3 mA electron beam. Fig. 6 illustrates the simulated small-signal gain for a 370-420 GHz, 10 dB gain, self-consistent, FWG-TWT amplifier design that we plan to use as the basis for proof-of-concept experiments. The gain calculations including loss in Fig. 6 assume conservative effective wall conductivity for copper of 3×10^7 S/m. From recent measurements of waveguide losses and cavity losses with micromachined circuits [11, 12], it is realistic to anticipate effective wall conductivities between 4 – 4.5×10^7 S/m at frequencies between 100 and 500 GHz. Computations show a saturated output power of 174 mW for a three cm long circuit.

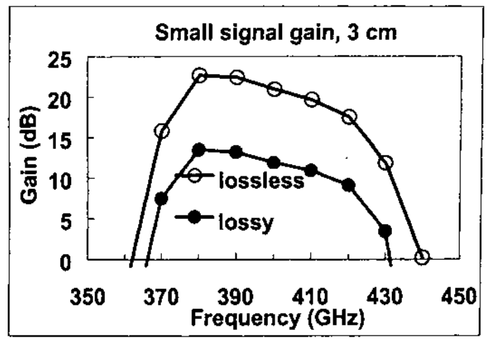

Fig. 6. Small signal gain for a three cm long FWG-TWT amplifier designed to operate at 400 GHz.

III. Experimental Investigations

We are experimentally investigating fundamental questions regarding FWG-TWT micro-VEDs for THz regime coherent sources. The FWG circuits are made in matching (mirror image) halves and bonded together to realize complete structures. Two processes for fabrication are under investigation. One approach, in collaboration with Argonne National Laboratory (ANL), is exploring the use of LIGA (a German acronym translated as lithography, electroforming, and molding) to fabricate the circuits. The other micro-fabrication process being investigated involves deep reactive ion etching (DRIE) of upper and lower halves of waveguide circuits in silicon substrates. A completed DRIE process will produce matching (mirror-image) circuit halves, which will appear as "trenches" in the silicon wafers, as shown in Fig. 7 for an illustrative 50 μm deep serpentine trench recently fabricated at the University of Wisconsin. Prior to bonding for FWG-TWTs, the insides of the trenches will be coated with copper and/or gold, and then bonded together to form a complete waveguide circuit. We will use a custom-designed 12 kV thermionic electron gun in a vacuum chamber to test these circuits in a 400 GHz proof-of-concept experiment.

Finally, the FWG-TWT oscillator with recirculated feedback is a new configuration, and its basic operating principles have never been previously explored. There are questions to investigate concerning its oscillation thresholds and equilibrium states. The FWG-TWT can have fractional instantaneous bandwidths as large as 10-30%, so it is interesting to determine what frequency (or frequencies) will be self-selected in the saturated oscillation state. The fraction of output power that is recirculated to the input will determine whether the device operates below start oscillation, at oscillation equilibrium, or in an overdriven state.

To investigate the fundamental physics of the recirculated FWG-TWT oscillator, we (in collaboration with Northrop Grumman) have assembled a 50 GHz scale model of the circuit, whose properties are currently under test.

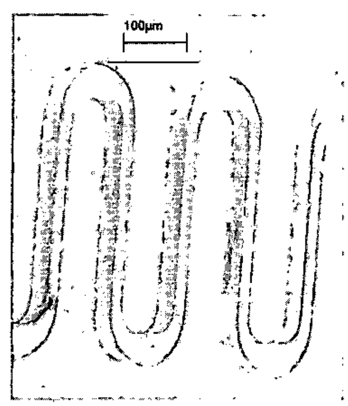

Fig. 7. Scanning electron micrograph of a serpentine trench etched in Si using DRIE. The trench cross sectional dimensions are approximately 50 mm X 50 mm.

IV. Conclusion

The terahertz (THz) region of the electromagnetic spectrum (~ 300 – 3000 GHz in frequency or ~ 0.1 – 1.0 mm free space wavelength) has enormous potential contingent, in part, on development of more powerful, efficient, compact, inexpensive coherent sources. Micromachined vacuum electron devices, or micro-VEDs offer a promising solution for compact, high power THz sources. The FWG-TWT has several attractive features, including high gain, substantial instantaneous bandwidth, high electronic efficiency, and a relatively simple circuit amenable to planar microfabrication processes. Thus, the FWG-TWT holds great promise for successfully realizing amplifiers and oscillators in the THz regime.

Acknowledgement

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