Operation of a Compact, 0.65 THz Source

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Abstract— **A compact, 0.65 THz vacuum electronic source based on micro-fabricated folded waveguide circuit technology has been demonstrated. The resonant circuits in the prototype devices were made using deep reactive ion etching. Several sources were built and operated between 0.605 and 0.675 THz. RF powers up to 98 mW were generated by the circuits, with a maximum of 50 mW measured outside the output window. Circuit interaction efficiencies of 0.45% were also achieved. These measurements were made at duty cycles up to 3%.**

I. INTRODUCTION AND BACKGROUND

COMPACT, efficient THz sources have been developed that generate RF power at the atmospheric window at 0.65 THz. This research was conducted as part of the DARPA Terahertz Imaging Focal Plane Array Technology (TIFT) program. A vacuum electronic (VE) device based on a folded waveguide (FWG) circuit was selected as the most promising approach. The viability of FWG sources has been demonstrated at Northrop Grumman, where a 40-55 GHz FWG amplifier that generated 50-135 W of output power was successfully operated [1]. A 3D representation of the circuit, including the RF input coupler, is shown in Figure 1. In the FWG circuit, a TE_{10} mode propagates through a serpentine, rectangular waveguide. The waveguide slows the RF phase velocity relative to the electron beam, enabling synchronous interaction and net gain. The FWG device has unique characteristics that make it attractive for THz operation. Its structure is planar, therefore simplifying the manufacturing process. The FWG circuit does not rely on fragile structures such as gratings to achieve amplification, and therefore it is more robust. It can be fabricated from a solid block for better thermal management. Finally, tapers at each end of the serpentine waveguide provide a natural and effective way for coupling power into and out of the circuit.

A number of technical challenges were resolved during the course of this program. The most significant was the implementation of precision micro-machining and integration approaches during the fabrication of the source. In low frequency VE devices, the circuits are large enough that they can be fabricated using conventional machining techniques. Above 100 GHz, these techniques become inadequate. The high operating frequency of the TIFT source also introduced other fabrication challenges. These included more stringent requirements for dimensional tolerance, surface finish, and alignment of the FWG structures. There were also major challenges associated with the electron beam. These included proper electron beam formation at the cathode, beam focusing, and high beam transmission with minimal loss through the FWG circuit to the collector.

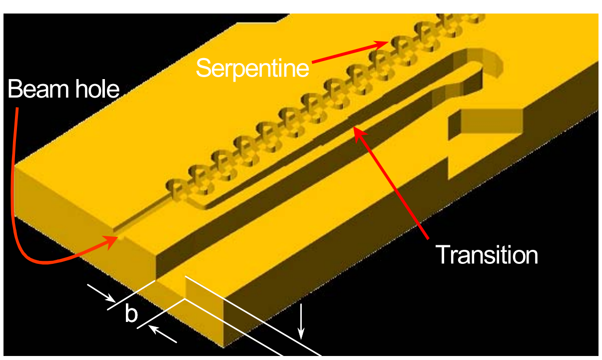

Figure 1- Folded waveguide structure

II. SOURCE MODELING AND FABRICATION

Because of the lack of a suitable RF driver at 650 GHz, it was decided to build a regenerative feedback oscillator rather than an amplifier for the first TIFT prototypes. In this configuration, the FWG section amplifies an input signal, and then a small fraction of the FWG output power is recirculated to the circuit input and re-amplified in order to maintain the oscillation. Stable operation occurs when the round trip gain is zero. The circuit phase velocity and interaction impedance were determined from HFSS simulations. The VE code CHRISTINE [2] was then used to calculate the interaction efficiency, total gain, and output power. The predicted output power at 650 GHz was 130 -160 mW. The actual output power was expected to be less because of RF losses in the output circuitry, and reduced beam current due to transmission losses in the circuit.

The electron gun is a critical component of a VE device. In the case of the TIFT source, it must provide a compact electron beam with high current density (>100 A/cm^2). We considered a number of options, including cold Spindt cathodes and thermal emitters based on LaB_6. We decided to use a conventional M-coated 411 dispenser cathode with an integral focus electrode. The cathode is operated at elevated temperature in order to achieve the required high current density.

Beam expansion in the FWG circuit was reduced by focusing the beam using a solenoid permanent magnet rather than the PPM stacks typically used in TWTs. The 10 kG field provided by the solenoid is much higher than required for Brillouin focusing. As a result, the beam is strongly confined, and radial beam excursions are small. MICHELLE 3D [3] was used to analyze the effects of misalignments and transverse magnetic fields on beam focus. Focus and transport of a 4 mA beam through the 60 x 60 μm^2 beam tunnel is a technical

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challenge as both axial and radial offsets can lead to significant interception of the beam. Because of the small size of the cathode, edge emitted electrons play a large role in the overall beam focus. Precision fabrication of the electron gun assembly, accurate mechanical alignment of the gun with the beam tunnel in the FWG circuit, and minimization of the transverse fields were used to achieve good beam transmission. A single-stage depressed collector was included to recover energy from the spent beam.

After comparing the available fabrication options, deep reactive ion etching (DRIE) was selected as the most promising technique. To make the circuit, a FWG trench is first etched into the Si substrates using a DRIE process. Trench depth is roughly half the desired waveguide height. A second etching process is then used to make the straight beam tunnel down the center of the circuit. The trenches are then coated with a blanket film of low-resistivity metal. Metal thickness exceeds a few multiples of the RF skin depth. Finally, the metallized substrates are aligned and bonded to form the FWG circuit. The bonded wafers are robust to subsequent dicing and assembly processes. Structures microfabricated with this technology can satisfy very challenging specifications, including high aspect ratios with very low sidewall roughness. Demonstrated capabilities include waveguide aspect ratios exceeding 8:1, height accuracy of 5%, height uniformity better than 1%, sidewall roughness of 50 nm, and an alignment accuracy of 2 um of the two FWG circuit halves.

III. RESULTS

The test set-up is shown in Figure 2. The THz source is

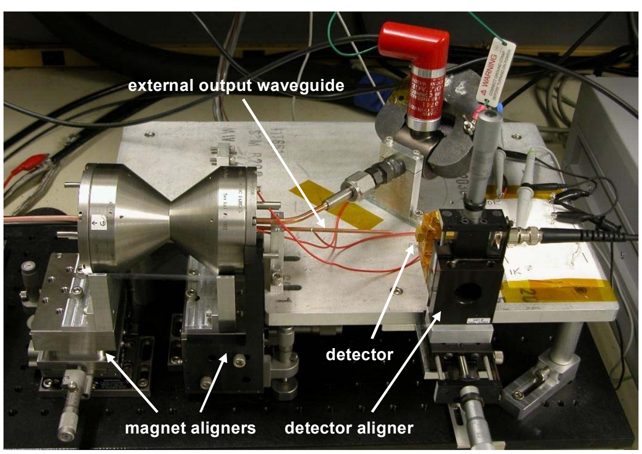

Figure 2 - TIFT source test setup

mounted on the test stand in the bore of the permanent magnet solenoid. Beam focus and transmission are controlled by the alignment of the magnet relative to the source, which is adjusted with two 3-axis translation stages. A cylindrical copper waveguide serves as an overmoded, external output waveguide to transmit RF output power to the THz detector. A 2L/s ion pump maintains the vacuum, and nitrogen gas flows through the magnet bore to stabilize the temperature of the source during testing. Finally, a diode detector and an Erickson Instruments calorimeter are used to measure RF output power, and a harmonic mixer is used to determine the oscillation frequencies.

A graph of the observed frequencies generated by the first source prototype is shown in Figure 3. Measurements indicate that the frequency of the FWG source step-tunes as the beam voltage is varied. Also shown is the theoretical frequency, which is determined by equating the beam axial velocity to the phase velocity of the RF wave through the FWG circuit. The measured frequency was found to decrease as the beam voltage increases. This is consistent with theory, as is shown in the graph. Power was observed in a sequence of steps from 607 to 675 GHz. At each frequency step, there was about 100-200 MHz of continuous tuning. The measured linewidth was less than 30 MHz. It is likely that some of this linewidth is due to fluctuations of the beam current and voltage during the pulse. The step tuning is the result of the feedback associated with the FWG circuit.

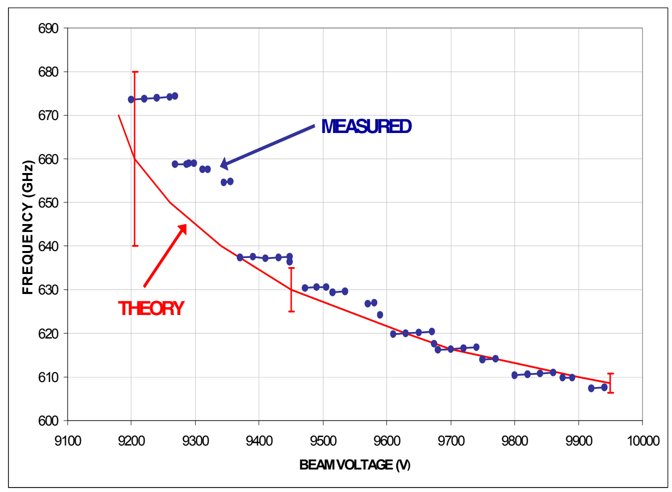

Figure 3 - Measured frequencies of TIFT source compared with theory

Four FWG source prototypes were tested during the TIFT program. Table 1 summarizes the experimental results for the final two sources. Source 3, when operating at 9.5 kV, oscillated at 0.656 THz. The RF power measured outside the BeO output window was 50 mW, a threefold improvement compared to earlier TIFT results. This improvement was primarily due to more current propagating through the circuit (2.1 mA versus 0.9 mA in the earlier source). Based on our calculations of the output waveguide and window losses, 89 mW was being generated by the Source 3 FWG circuit. The frequency was observed to step-tune as the beam voltage was varied from 9.5 kV to 10 kV. The beam transmission during high power operation was 45%. The single-stage depressed collector could be operated at 8.8 kV, so a significant fraction of the energy of the spent beam could be recovered. However, because more than half of the beam was lost due to interception, the overall source efficiency was only 0.19%.

Our goal for Source 4 was to increase the overall efficiency by improving beam transmission. We slightly increased the cross section of the beam tunnel to reduce wall interception, and we reduced field errors of the solenoid through the use of shims. Calculations indicate that errors as low as 10 Gauss can cause a significant beam deflection. Transmission did significantly improve in Source 4, with 79% of the 4.7 mA beam reaching the collector. However, the lower interaction impedance associated with the larger beam tunnel did lower the circuit efficiency to 0.27% from 0.45%. We also had fabrication difficulties with Source 4. The folded waveguide was overetched, and as a result the operating frequency was shifted from the goal of 0.65 THz to 0.59 THz. Although the circuit was able to generate significant power at this frequency (98 mW), our model of the window indicated that half of the RF power was reflected and lost. As a result, only 27 mW was measured outside the window. If the circuit had been etched to the proper depth and operated at the correct frequency, then 55 mW would have been measured outside the window, and the source efficiency would have been 0.47% based on a depressed collector voltage of 9.3 kV. This is significantly higher than the 0.19% achieved with Source 3, and is primarily the result of better beam transmission. If output circuitry losses are neglected, and the power at the FWG circuit is used, then the source efficiency is 0.8%.

IV. CONCLUSIONS

A VE oscillator based on a FWG circuit has been successfully operated between 600 and 675 GHz. RF powers up to 50 mW were measured at the output window, corresponding to a circuit efficiency of 0.45%. This significantly exceeds the capabilities of existing compact sources operating at these frequencies. Operation at duty cycles up to 3% have been demonstrated. The FWG circuit used to maintain resonance between the electron beam and RF wave was fabricated using DRIE technology. This represents one of the first implementations of silicon-based technology to vacuum electronics. The excellent performance of the source indicates that the challenging dimensional and alignment requirements can be met with existing micro-fabrication processes. Our FWG models indicate that this source technology can be extrapolated to other frequencies between 0.2 and 1.0 THz.

Table 1 - TIFT Source Operating Parameters

PARAMETER	**Source 3**	**Source 4**
Frequency (THz)	0.656	0.595
Power @ circuit (mW)	89	98
Power @ window (mW)	50	27
Gain (dB)	~ 21	~ 15
Beam voltage (kV)	9.5	10.0
Pulse length, max. (ms)	1.0	0.5
Repetition rate, max. (Hz)	30	2
Duty cycle, max. (%)	3	0.1
Axial field (kG)	10	10
Emission current (mA)	4.6	4.7
Collector current (mA)	2.1	3.7
Beam transmission (%)	45	79
Circuit efficiency (%)	0.45	0.27
Source efficiency (%)	0.19	0.23

V. ACKNOWLEDGEMENT

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