Integrated Terahertz Transmit / Receive Modules

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***Abstract* — We report on research and development of millimeter-wave components used in prototype 600 GHz transmit and receive systems. These systems offer state-of-the-art performance in terms of noise, power, ease of use and mechanical and electrical robustness. The transmitters comprise high-power frequency multiplier chains driven by commercial power amplifiers in the 18-45 GHz range and lower frequency fundamental oscillators. The receivers comprise a subharmonic mixer and an LO multiplier chain. All of the components are based on planar GaAs Schottky diodes in fixed-tuned broadband embedding structures. These designs are scalable to any frequency in the band from 100 GHz through 1 THz and we are exploring the challenges of scaling to the 1-5 THz band.**

I. Introduction

The millimeter- and submillimeter-wave portion of the electromagnetic spectrum is of great commercial and scientific interest. Many important molecules resonate in this band and thus can be remotely detected with an appropriately designed radiometer. This is important for applications such as chemical spectroscopy, studies of Earth's upper atmosphere, radio astronomy, weather monitoring, and the remote sensing of biological and chemical toxins.

The terahertz band offers nearly unlimited bandwidth for wireless communications systems as well as increased security for point-to-point communications. Other applications include medical diagnostics, landing and collision avoidance radars that penetrate smoke and fog, high-resolution radar and compact-range radar.

Full utilization of this band has been impeded by the lack of suitable components for signal generation and detection. Fundamental oscillators operating in this regime tend to exhibit some combination of low-power, high-noise, narrow-bandwidth, large size, or multi-moded operation. An alternative signal generation technique is to combine a lower frequency low-noise microwave source with a chain of frequency multipliers. Historically, frequency multipliers operating above 100 GHz comprise a whisker-contacted diode and one or more mechanical tuners that must be adjusted at each frequency. Although this technique has been successful, the lack of power-handling and frequency agility of the multipliers has been a limiting factor.

In this research we have replaced the whisker-contacted diode with a much more mechanically robust planar device mounted on a high thermal conductivity substrate. We have also eliminated all of the mechanical tuners and yet maintained a relatively large fixed-tuned bandwidth. This means that the user may adjust the frequency electronically. These new frequency multipliers exhibit not only significantly higher power handling and fixed-tuned bandwidth, but also greater reliability and repeatability.

II. 600 GHz Receivers

A range of broadband receivers has been developed with RF bands ranging from WR-8 (90-140 GHz) to WR-1.7 (440-660 GHz) [1]. The subharmonic mixers use an LO at half the RF, and also provide LO noise suppression. Measurements at 640 GHz on a WR-1.7 subharmonic mixer have yielded a mixer noise temperature of 1550 K (DSB) and a conversion loss of 9 dB (DSB) using only 4 mW of LO power at 320 GHz. Typical WR1.7SHM performance is shown in the graph in Fig. 1. A WR1.2 mixer covering 600-900 GHz is currently under development.

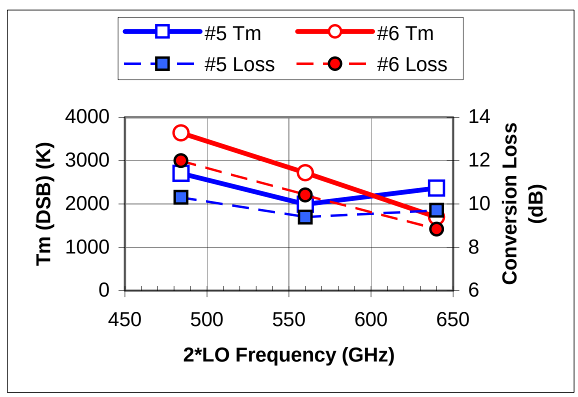

Fig. 1. Measured subharmonic mixer noise temperature and conversion loss of the WR1.7SHM. The LO power ranged from 2-6 mW in the band 240-320 GHz.

We are also integrating LO frequency multipliers with the subharmonic mixer to further reduce the LO frequency requirement. Our WR5.1x3SHM incorporates an LO frequency tripler in the mixer waveguide block. The RF band is 150-215 GHz, the LO band is 25-36 GHz and the IF bandwidth is approximately 13 GHz. For water vapor measurements at 183 GHz we have measured a mixer noise temperature of 530 K DSB and a conversion loss of 5.1 dB DSB using a 100 mW LO near 30 GHz. Noise and conversion loss data in the RF band from 150-200 GHz is shown in the graph in Fig. 2. The WR5.1x3SHM mixer performs as a true second harmonic mixer rather than a sixth harmonic mixer because the integral tripler delivers a clean third harmonic LO signal to the second harmonic mixer.

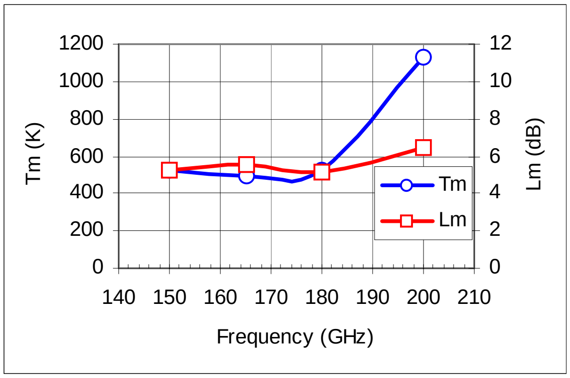

Fig. 2. Initial measurements from the first build of a WR5.1x3SHM subharmonic mixer with integrated LO tripler. The LO signal is about 100 mW in the band 25-34 GHz. Noise and conversion loss are double sideband (DSB).

We are also developing a line of zero biased detectors that use a low barrier height semiconductor. Our WR6.5ZBD zero bias detector has achieved a responsivity of over 5500 V/W at 150 GHz.

III. High Power Frequency Doublers

We have developed a line of high-power varactor frequency doublers with output frequencies in the range from 40-650 GHz. These are balanced doublers [2-4] employing high-power optimized Schottky varactor chips with multiple anodes in an anti-series arrangement. The typical fixed-tuned bandwidth is approximately 15% of the band center frequency. Higher fractional bandwidths are possible by reducing the Q of the input embedding circuit and thus lowering the multiplication efficiency.

We have now demonstrated in excess of 700 mW near 50 GHz, 300 mW near 100 GHz and 100 mW near 150 GHz as indicated in Fig. 3. These power levels do not represent fundamental limits and we are currently developing techniques for further improvement. First order thermal models indicate that our high thermal conductivity substrates efficiently conduct heat away from the device.

When used in conjunction with a lower frequency low noise fundamental oscillator, the power level, single moded output and fixed-tuned bandwidth of these doublers make them an attractive replacement for high frequency Gunn oscillators, IMPATTS and backward wave oscillators.

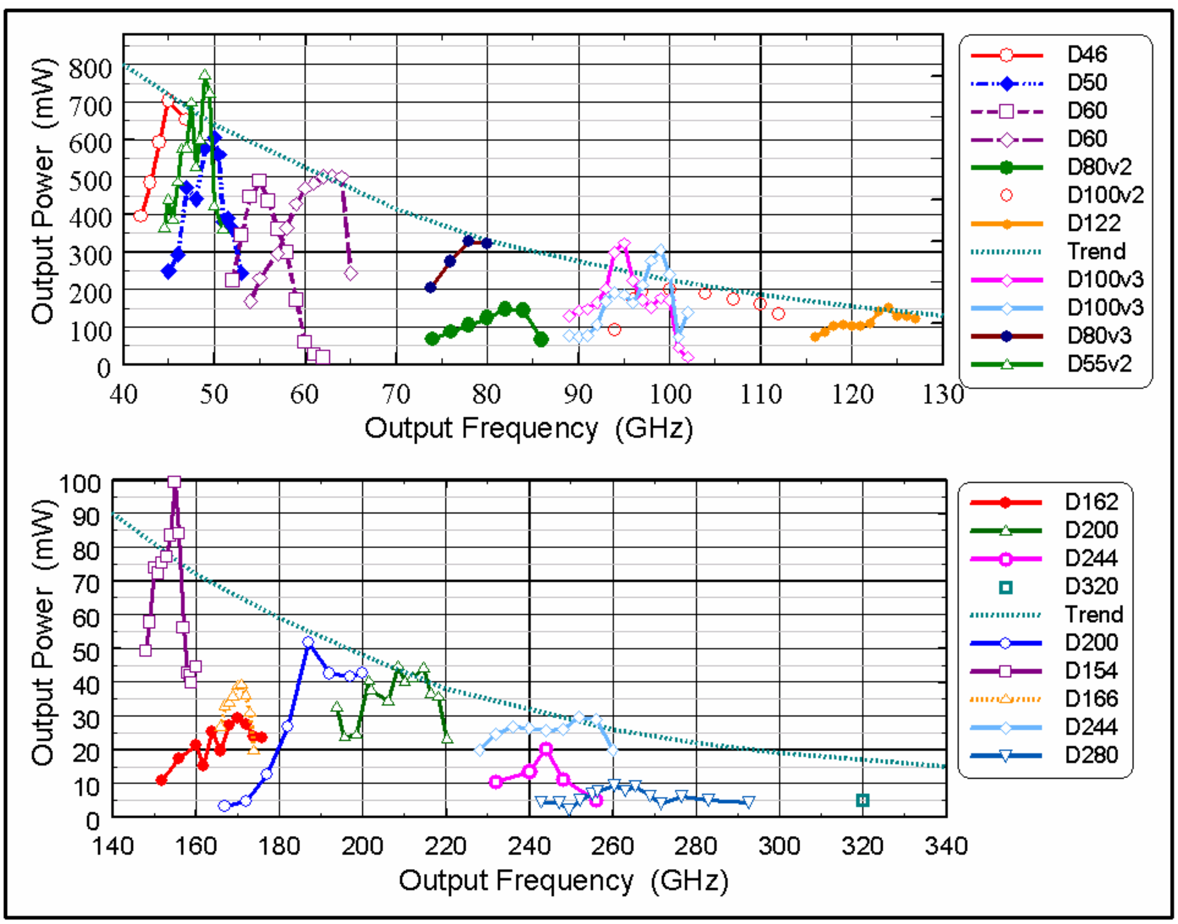

Fig. 3. Summary graph showing measured output power from a wide range of VDI high-power frequency doublers. All of the doublers are fixed-tuned (i.e. no mechanical tuners of any kind were used).

IV. Full Waveguide Band Frequency Multipliers

With planar and integrated diodes and modern circuit design tools, it is also possible to create full waveguide band frequency doublers, triplers and quintuplers operating well above 100 GHz. Our broadband doublers are based on anti-series and series topologies. Doublers using anti-series arrangements and careful circuit design can suppress third harmonic propagation. The triplers and quintuplers are based on topologies that naturally suppress even harmonics and thereby maximize tripler and quintupler efficiency.

The Schottky diodes in the triplers and quintuplers are electrically isolated from the waveguide block and are thus highly resistant to electrostatic discharge (ESD). Fig. 4 shows output power from our WR2.8x3 tripler driven at 20 mW and 50 mW. This tripler has no bias requirement and can be tuned electronically to any point in the band.

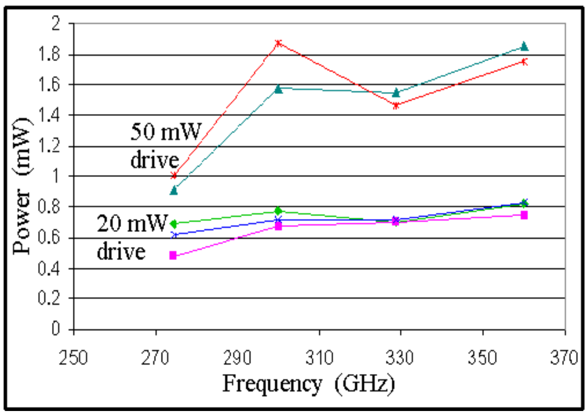

Fig. 4. Measured WR2.8x3 tripler output power. The tripler may be swept electronically to any frequency in the band.

We are developing techniques to increase the power handling of our full-waveguide band multipliers so that they produce sufficient power to drive a follow-on cascaded frequency multiplier. Our WR12x2 doubler uses an array of planar varistor diodes to produce greater than 35 mW across the band 60-90 GHz when driven with 300-400 mW from an amplifier in the band 30-45 GHz. The WR12x2 has been driven with 900 mW for several days, producing over 120 mW output power with no measurable degradation. We have also driven the WR12x2 with 1.2 W for several seconds with no measurable damage. We use the same materials and techniques in the WR12x2 to channel heat from the varistor chip that we use in our high-power varactor doublers.

We have cascaded a full-band WR6x2 (60-90)/(120-180) GHz doubler to the WR12x2 to create a quadrupler with greater than 1 mW across the band from 120-180 GHz and greater than 5 mW across the band from 128-172 GHz as shown in Fig. 5. In a new design we are combining these doublers in a single waveguide housing with the goal of achieving greater than 5 mW across the band.

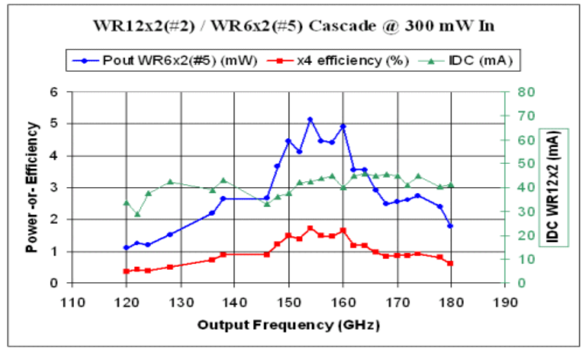

Fig. 5. Measured output power for the WR12x2/WR6x2 cascaded pair. The doublers were attached without using an isolator. No mechanical or electrical tuners were used.

We recently integrated the WR12x2 frequency doubler and a WR4.3x3 tripler into a single block designated as a WR4.3x6 sextupler. Fig. 6 shows a block diagram of the sextupler. The DC current in the first-stage doubler may be externally monitored, providing a good measure of power in the system.

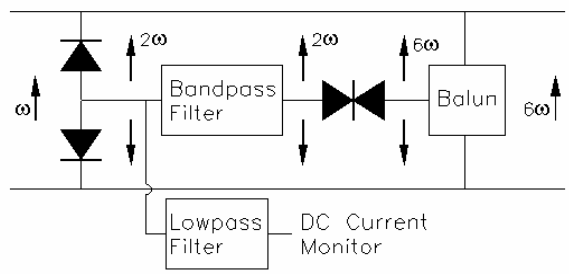

Fig. 6. Schematic diagram of the VDI model WR4.3x6 frequency sextupler.

Measured WR4.3x6 sextupler output power is shown in Fig. 7. The input drive levels for this measurement range from 200-500 mW in the band 30-45 GHz. Each frequency sweep contains over 50 data points. There are no nulls or severe dips in the output power over the entire operating band. The sextupler does not employ any mechanical or electrical tuners and no DC bias is required. The frequency may be instantaneously swept to any point in the band.

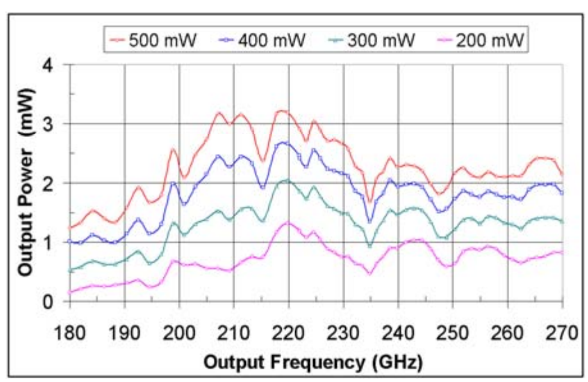

Fig. 7. Measured output power for the WR4.3x6 frequency sextupler. The frequency resolution is approximately 2 GHz.

V. 600 GHz Transmitters

Our goal for the 600 GHz transmitter is to produce 5-10 mW with greater than 10% fixed-tuned bandwidth. We are experimenting with two approaches both of which are based on cascaded planar varactor multiplier chains.

1. x2x2x2x3 = x24 - three varactor doublers that drive a final stage varistor tripler.
2. x2x2x2x2 = x16 - four varactor doublers.

High-power MMIC amplifiers at 25 GHz for the x24 chain and 38 GHz for the x16 chain are commercially available with output power greater than 2 W and gain in excess of 35 dB. Thus the required drive level from the fundamental oscillators is less than 1 mW.

The x24 multiplier chain uses VDI model D55v2, D100v3 and D200 doublers. Measured output power for these doublers is shown in Fig. 3. In our initial tests of the x24 chain we have achieved almost 700 μW at 588 GHz as shown in the graph of Fig. 8. The tripler was not optimized for this application and a redesign is underway to improve power handling and efficiency.

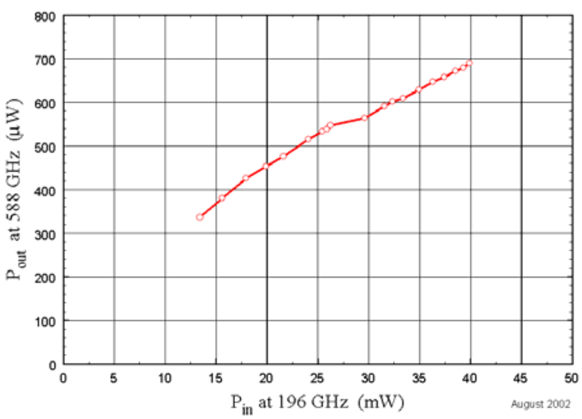

Fig. 8. Measured output power from the prototype x24 frequency multiplier chain. The power at 196 GHz was measured through a directional coupler.

The x16 all varactor doubler chain should produce more power at 600 GHz than the x24 chain. We have completed the designs of the first two doublers in the chain, the D80v3 and D154. Measured output power from the D154 is about 100 mW as shown in the graph of Fig. 3. We are currently designing a new ID300 (Integrated Doubler to 300 GHz) for the x16 chain. The ID300 will comprise multiple varactors in antiseries on a high-thermal conductivity substrate. The projected efficiency is greater than 20% and the estimated output power is close to 20 mW.

We have already completed the design of the ID600, a new integrated 600 GHz varactor doubler. The ID600 utilizes GaAs on quartz integration [5]. Although quartz is a poor thermal conductor, the power handling requirements for this device are fairly moderate. A first order thermal model of the ID600 circuit indicates that the device will operate within 25 degrees of ambient even in the worst case scenario when all of the 20 mW input power is resistively dissipated in the epitaxial layer near the anodes. The ID600 is currently being fabricated and should be ready for assembly and testing in July or August. We hope to present data for the entire x16 chain to 600 GHz at the conference in October.

VI. Conclusion

Planar diode technology when combined with modern computer aided design tools and clever circuit design make possible the development of fundamentally improved frequency multipliers and mixers in the millimeter and submillimeter wavelength bands. Through this work we have demonstrated significantly improved noise performance, power levels and fixed-tuned bandwidth over a wide range of frequencies. These components are also considerably more robust than the older whiskered-diode technology, have greater uniformity and repeatability and are much more easily arrayed for balanced circuit topologies and high power applications.

Since none of these components use any type of mechanical tuner they may be swept instantly to any point in their frequency band. The single-moded output, power level and fixed-tuned bandwidth of the frequency multipliers make them an attractive replacement for high frequency Gunn oscillators, IMPATTS and backward wave oscillators.

Acknowledgements

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References

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