A Sub-Picosecond Phase Stability Frequency Multiplier

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***Abstract* ---- A UHF to S-band (476 MHz to 2.856 GHz) frequency multiplier exhibiting sub-picosecond thermally induced phase drift has been developed. The new multiplier also exhibits unusually low residual phase noise.**

I. INTRODUCTION AND BACKGROUND

The development of a sub-picosecond phase stable frequency multiplier was motivated by performance requirements needed to further the state of the art in linear accelerator synchronization. Existing multipliers exhibit phase drift due to temperature variations that far exceed the specifications of the distribution system. As an example, the existing multipliers used in the SLAC 2-mile linac have temperature coefficients as much as 4 degrees/°C at 2856 MHz (about 3900fS/°C) [1]. The Next Linear Collider requires phase stability on the order of 100fS in the RF which is distributed at 357 MHz over 30 kilometers with 50 distribution points every 600 meters [2]. A single such multiplier experiencing a 20 degree ambient temperature variation would introduce a phase shift 700 times greater than is acceptable. Feedback stabilization techniques are employed to reduce the error but lower drift multipliers reduce the loop gain required to stabilize the beam phase, increasing the stability margins.

Various multiplier topologies, filter types and components were studied to develop an inherently stable circuit that also exhibits low phase noise and a new bootstrapped oven structure was designed to tightly control the temperature of the circuitry. The discoveries were combined in two prototype units that exceed the design goals.

II. MULTIPLIER TOPOLOGY

The factor-of-6 multiplication was performed in two stages, 3X and 2X, to allow the selection of topologies that exhibit inherent phase stability. The Wenzel odd-order topology shown in Figure 1 inherently switches at zero-crossings, depending only on diode matching [3].

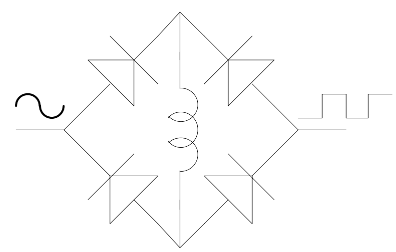


Figure 1. Wenzel Odd-Order Topology

The common diode doubler circuit also tends to reject amplitude and temperature induced phase shift in a similar manner. Other multiplier topologies that were rejected as candidates had non-zero thresholds that would cause significant AM to PM conversion and were expected to exhibit significant threshold temperature coefficients.

III. EXPERIMENT TEST BED

The majority of the experiments were performed with a 3X multiplier with a 1500 MHz output. A 500 MHz source consisting of a 100 MHz low noise ovenized oscillator, a high-level 5X frequency multiplier, amplifier and attenuators was constructed (Figure 2).

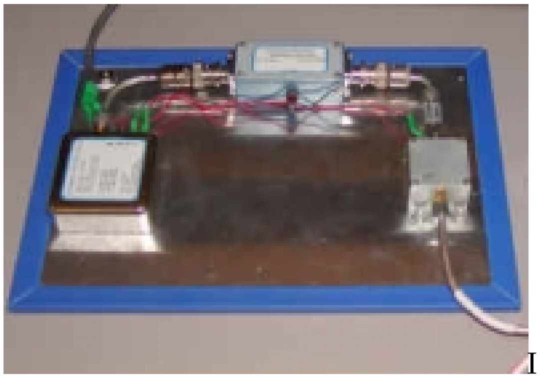


Figure 2. 500 MHz Test Source

It was realized from the outset that the temperature coefficients of the test bed components, test equipment and cables would create significant measurement problems due to changes in the room ambient temperature. To minimize these problems, the reference frequency power splitter, reference multiplier and phase comparison mixer and low-pass filter were ovenized (Figure 3).

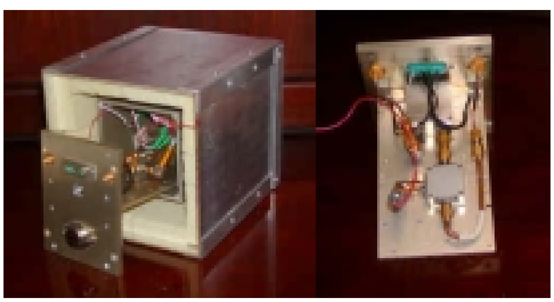


Figure 3. Reference Path Oven

Heater transistors were mounted on all faces of a 1/4" thick aluminum case for even heat distribution and the sensing thermistor was located at the junction of the front connector plate and the internal mounting plate to bootstrap the internal plate temperature. The oven controller is on the bottom side of the internal plate and the whole oven structure is surrounded by foam insulation. Room is available on both sides of the internal plate for all of the reference leg components including the power splitter, mixer, and multiplier. Figure 4 shows the initial test configuration, including the temperature chamber. Preliminary temperature tests with only two semi-rigid cables and a connecting SMA bullet in the chamber showed a phase drift of about 0.7pS that would vary unpredictably from one run to the next, making 0.1pS resolution measurements impractical. Further experiments led to the conclusion that the necessary bends in the cable due to the chamber's single access port, the connectors, and the cable design all contributed to the phase instability.

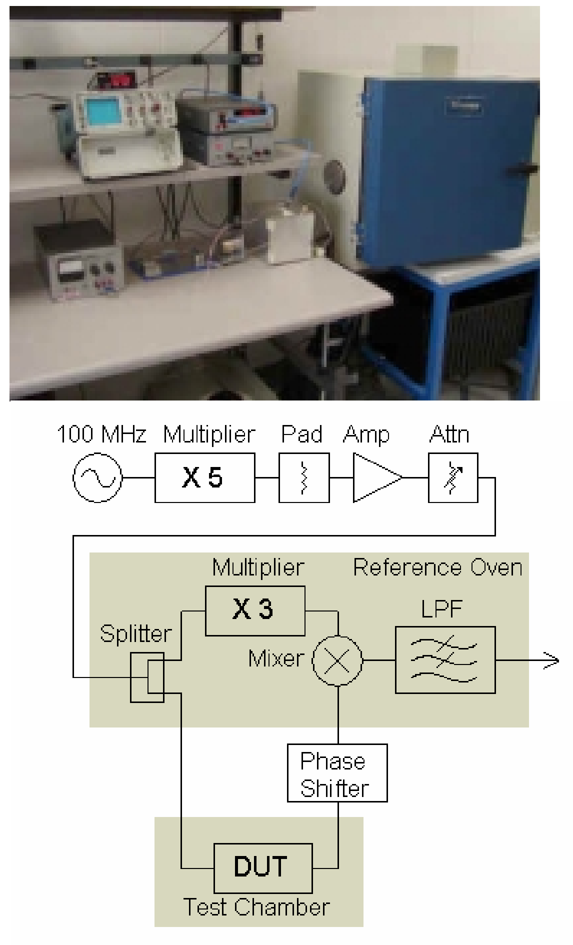


Figure 4. Initial Test Bed

A single loop of temperature-cycled Gore ReadyFlex .145 cable with no connectors in the Tenney Jr chamber exhibited about 0.1pS of somewhat predictable phase drift but an order of magnitude improvement was desired. To minimize the amount of cable exposed to the temperature variation, a small thermoelectric temperature chamber was constructed with holes for cables at each end to avoid bends (Figure 5). A test with low phase drift cables (Storm Products, Phase Master 190) and a low phase drift Astrolab #29485-3 SMA bullet gave a phase shift of only 0.02ps from 20°C to 50°C and little hysteresis was observed.

IV. ODD-ORDER MULTIPLIER TESTS

A quick test with both the two diode and four diode versions of the Wenzel odd-order multiplier topology suggested that the four diode version exhibited significantly less drift, changing only 5.6pS over a 20 degree range, about 1/3 the phase drift of the two diode version. Individually heating opposite polarity diodes in the four diode version produced opposite polarity phase drift, suggesting that compensation was occurring, as expected.

Figure 5. Thermoelectric Chamber

A standard four-diode times three, 500 to 1500 MHz, Bluetop multiplier (with lumped-element filters and MMIC amplifier) was tested in the new chamber from 30°C to 50°C. The phase drift was 10pS with good repeatability. Another version of the four-diode multiplier featuring a tapped hairpin microstrip bandpass filter on Taconic RF60 circuit board material drifted 8.6pS over the same temperature range (Figure 6).

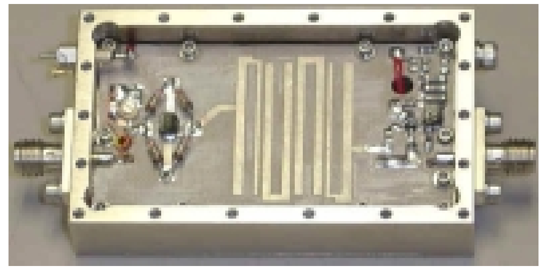
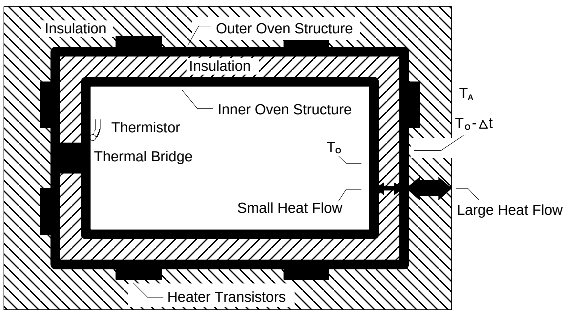


Figure 6. Multiplier with Microstrip Filter

Testing the microstrip filter without the multiplier diodes yielded 13pS drift suggesting that some cancellation was occurring in the multiplier. Another ceramic element filter was constructed and tested at 500 MHz and the drift was 5.5pS. A lumped-element bandpass filter at 1.5 GHz exhibited about 5.0pS drift. These two filters are within practical ovenization range, requiring a modest oven gain of 50 to achieve 0.1pS stability, and are considerably smaller than the microstrip filter. A Lark Engineering 2.856 GHz dielectric filter, P/N 45D2856-50-3CC, was tested from 20°C to 40°C with excellent results, drifting only 1.7pS, requiring only modest temperature control to stabilize. The overall performance of the odd-order portion of the multiplier was projected to be less than 10pS, requiring an oven gain of 100 or better.

V. BOOTSTRAPPED OVEN

Traditionally, nested, double-oven temperature controllers have been used when unusually precise temperature control is needed, offering thermal gains in the thousands [4]. But, double-ovens are avoided when possible; nesting oven controllers adds significant complexity usually requiring careful adjustment by trained technicians and, since the inner oven must operate at a temperature above the outer oven, the inner oven must operate at a significantly higher temperature than a single-oven for any given ambient temperature. Wenzel has previously developed a proprietary bootstrapped oven technique that approaches the performance of a double-oven without the circuit complexity or elevated temperature requirements. In the simplest implementation, inner and outer oven cans made of a thermally conductive material are thermally connected at one point or along an isothermal line and insulated from each other at all other points (Figure 7). The temperature



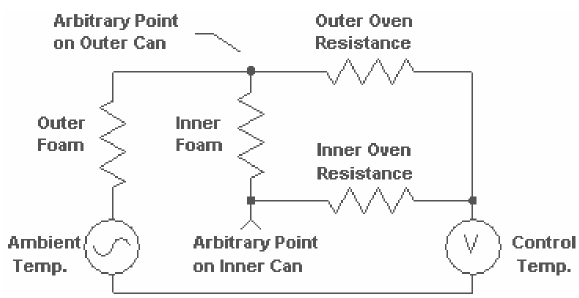


Figure 7. Bootstrapped Oven Scheme

sensor, typically a thermistor, is located at or near this connection point so that its temperature is precisely controlled, represented as a fixed control temperature, V, in the electrical analog. (The thermistor optimum position might be slightly toward the ambient to compensate for finite open-loop gain.) The heat is applied to the outer oven by semiconductors or resistive heater elements. Since the outer oven can is approximately isothermal (outer oven resistance is low compared to outer foam resistance) and nearly the same temperature as the inner oven can, little heat flows through the insulation between the cans and, consequently, little thermal gradient is present on the inner oven. In essence, the outer oven can bootstraps the cold side of the insulating foam between the cans, substantially raising its effective thermal resistance. Since the thermal resistance of the insulation is several orders of magnitude above the resistance of the oven structures, ambient temperature changes are attenuated by a factor equal to the product of the ratio of the outer oven structure thermal resistance to the outer foam thermal resistance and the inner oven structure thermal resistance to the inner foam thermal resistance. Experiments at Wenzel Associates have shown improvements of a factor of 50 for a simple copper "blanket" wrapped over the target device and connected to the outer oven near the thermistor location. Greater improvement has been realized in a high-performance oven oscillator that exhibits a thermal gain over 500, employing a PCB made from Bergquist Thermal Clad material as the inner oven structure. This PCB is a 0.060 layer of solid copper with an insulating layer and traces on one side. The PCB has three mounting points but only one allows direct thermal contact with the outer oven and the control thermistor is located at this point. A similar approach was used for the multiplier except that a separate copper sheet was reflowed onto the bottom side of the PCB.

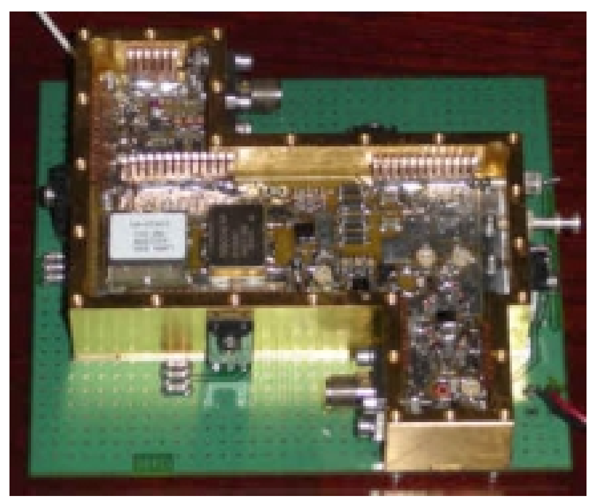


Figure 8. Multiplier Circuit and Oven

Figure 8 shows the oven structure with the lid removed, exposing the multiplier. The odd shape brings the RF connectors further into the oven environment to reduce their contribution to phase drift and to reduce point cooling due to the cables. The inner oven structure is a .05” copper plate that is reflow-soldered to the bottom of the PCB and it makes contact with the outer oven can at one point near the control thermistor. This first attempt at the board had RF grounding problems that required the addition of grounding contacts. These contacts tend to defeat the bootstrapping and are undesirable. The second version eliminated most, but not all, of these fingers and any future upgrade will eliminate them entirely by completely shielding each RF section with a local electrostatic cover. Figure 9 shows the oven inside an insulated housing. The bulk of the insulation is rigid urethane foam but the higher surface areas of the top and bottom have an additional ¼ inch flexible Aerogel blanket, P/N 100002, manufactured by Aspen Aerogels (not shown). The insulation scheme is effective; the measured thermal resistance of the oven is approximately 22.6°C/watt which is high for an oven of this size.

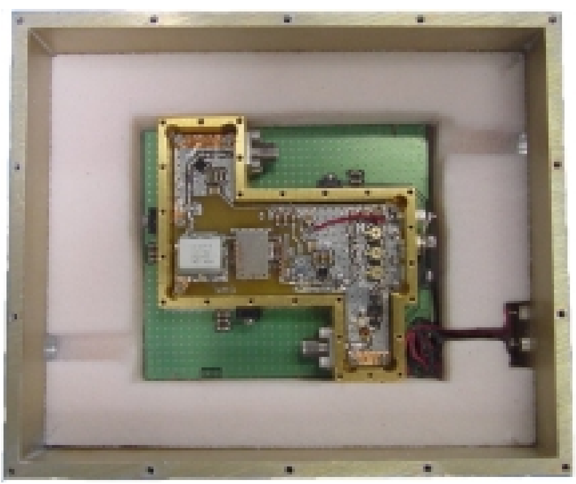


Figure 9. Multiplier with Lids Removed

VI. PROTOTYPE TESTS

A Delta Design MK2300 temperature chamber was modified by drilling a hole through the back to avoid bending the cables and to minimize the amount of cable in the chamber. The finished units were too large for the original homemade chamber. The test setup includes an automatic data acquisition system (figure 10).

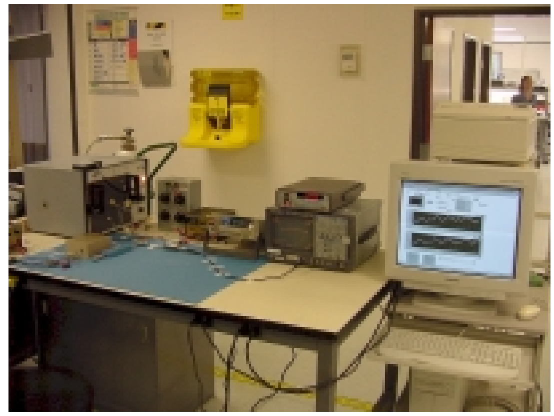


Figure 10. Prototype Test Bed

Two identical multipliers were constructed for testing in a manner similar to the technique shown in figure 4. Preliminary tests could not detect any systematic phase drift attributable to the multipliers but the test system exhibited significant wander and hysteresis due to cables and components exposed to the room ambient. It was determined that a more successful approach to quantifying the multipliers’ drift was to change the set-point of the multiplier’s oven to cause a fixed, known temperature step and to measure the resulting phase shift. Then, by measuring the actual gain of the oven controller, the phase drift due to an ambient temperature change could be inferred with a reasonable degree of accuracy. The oven set-point of one unit was varied in 10 ohm steps for a total of 50 ohms which results in a total set-point temperature change of 1.85°C. Figure 11 shows the response to one of the 10 ohm steps, indicating a phase change of 0.37pS for a temperature change of 0.325°C. The sensitivity of this unit is thus 1.14pS/°C. The phase drift for each step and the total span were in close agreement.

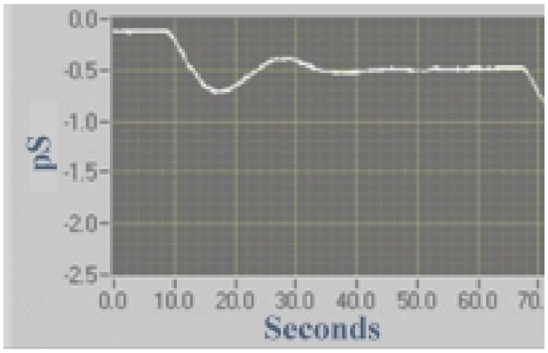


Figure 11. Phase due to Oven Temp Steps

The oven gain of this unit was determined to be 435 by measuring the temperature change on the inner oven plate as the test chamber temperature is varied 20°C. The total drift predicted for the 20°C ambient change is thus:

$$\frac{1.14\text{pS} \times 20}{435} = 0.052\text{pS}.$$

The other unit was projected to have a drift of 0.057pS in the same manner.

The residual phase noise of the two units was measured using the setup shown in figure 4. Assuming both units contribute equally, the input-referred single-sideband noise floor is -170dBc and the flicker intercept is -127dBc. Significant rejection of the reference's noise is expected with the residual noise test but the contribution of the reference's noise was not determined.

VII. CONCLUSION

A UHF to S-band (476 MHz to 2.856 GHz) frequency multiplier exhibiting less than 0.1pS thermally induced phase drift has been developed. This unprecedented stability was achieved by the selection of low phase drift filters and multiplier topologies and by a novel Aerogel insulated, bootstrapped temperature controller. Further improvements could be realized by adding electrostatic shields to the PCB to eliminate the need for grounding fingers that tend to spoil the temperature bootstrapping.

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