National Aeronautics and Space Administration

High Efficiency Subharmonic Mixing MMIC for Space-based Atomic Precision Spectroscopy

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Objectives:

We investigate using an III-V semiconductor based nonlinear transmission line (NLTL), acting as a high multiplication ratio subharmonic mixer, to obtain >-55 dBm output power at ~40.5 GHz when matched to a 50-ohm output load, while also using significantly less DC power than preexisting step recovery diode (SRD) approaches. We also investigate using a flight FPGA as a direct digital synthesizer (DDS), to produce a finely-controlled tuning frequency, which when mixed with a suitable radio-frequency (RF) tone provides fine frequency control of the final output tone.

Background:

Precision atomic and molecular spectroscopy enables quantum-physics-based missions such as Deep Space Atomic Clock (DSAC), Cold Atom Laboratory (CAL), and many proposed/undergoing quantum computing and communications and sensors projects. High spectral purity and tunable microwave synthesis has been commonly utilized in precision spectroscopy, but their size, weight and power limits use of these quantum-based instruments for CubeSat-based missions, miniaturized instrumentation to deep space as well as use in sub-millimeter wavelength Rydberg spectroscopy for quantum sensing. SRDs use several watts, and a phase-locked dielectric resonating oscillator and multipliers use yet more[1].

Approach and Results:

Given this application's sensitivity to close-in flicker noise, and since most III-V semiconductor-based solutions offer superior power performance to a Silicon-based SRD solution, we pursued an InGaP build. This selection offers more accurate nonlinear diode models (compared to GaN).

We elected to use 10 identical copies of a unit cell for time savings. The unit cell is depicted below in Figure 1, and creates intentional dispersion so as to generate a sharp rising/falling edge, and hence high harmonic content [2]. The inductor & resistive values were ultimately optimized for the particular diode models [2]. The diodes' self-rectification provides the required DC bias, as shown in Figure 1.

Compared to empirical SRD frequency synthesis and a commercial-off-the-shelf (COTS) Marki Microwave NLTL-6026 (Figure 3-b), we obtained a competitive max output power of -43 dBm at 40.507 GHz with this design when using equivalent input frequencies and powers (Figure 3-a). In practice, a real circuit would output a few dB lower power with realistic lossy input and output networks.

In parallel, we investigated the feasibility of obtaining a fine-tuning adjust frequency via an FPGA-derived direct digital synthesis (DDS). In most test cases, the DDS phase noise is >20 dB below the relevant DSAC requirement, suggesting the noise will be low enough for most atomic/molecular spectroscopy applications. While DC power was high, it could be reduced substantially with a more refined build. The current build exhibits a tuning resolution of 1.5 mHz when using a 100 MHz reference frequency, providing 3.7e-14 frequency control at the target frequency for DSAC.

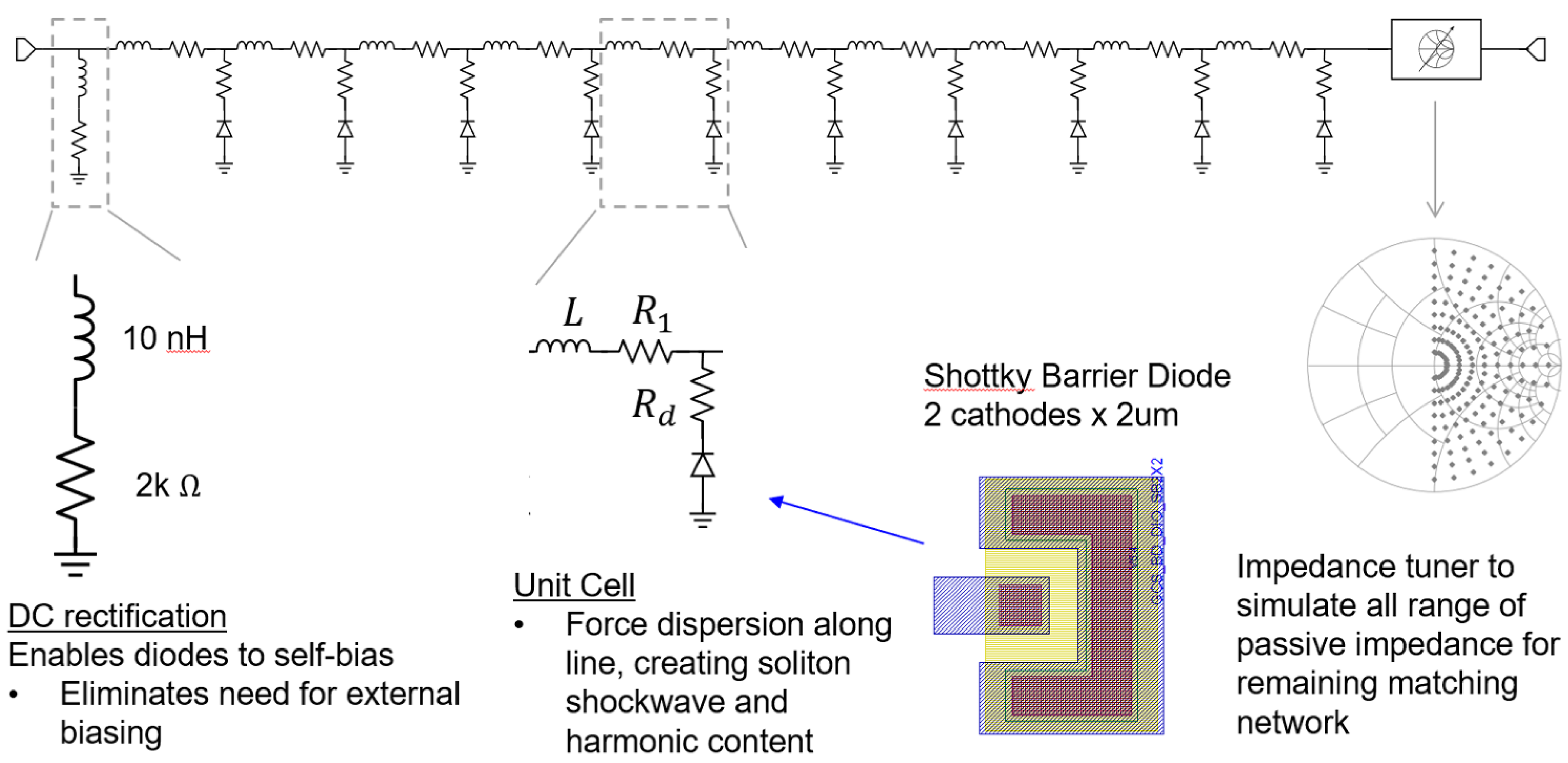

Figure 1: NLTL schematic, with unit cell construction, input self-biasing, and an output impedance tuner working to provide an ideal output

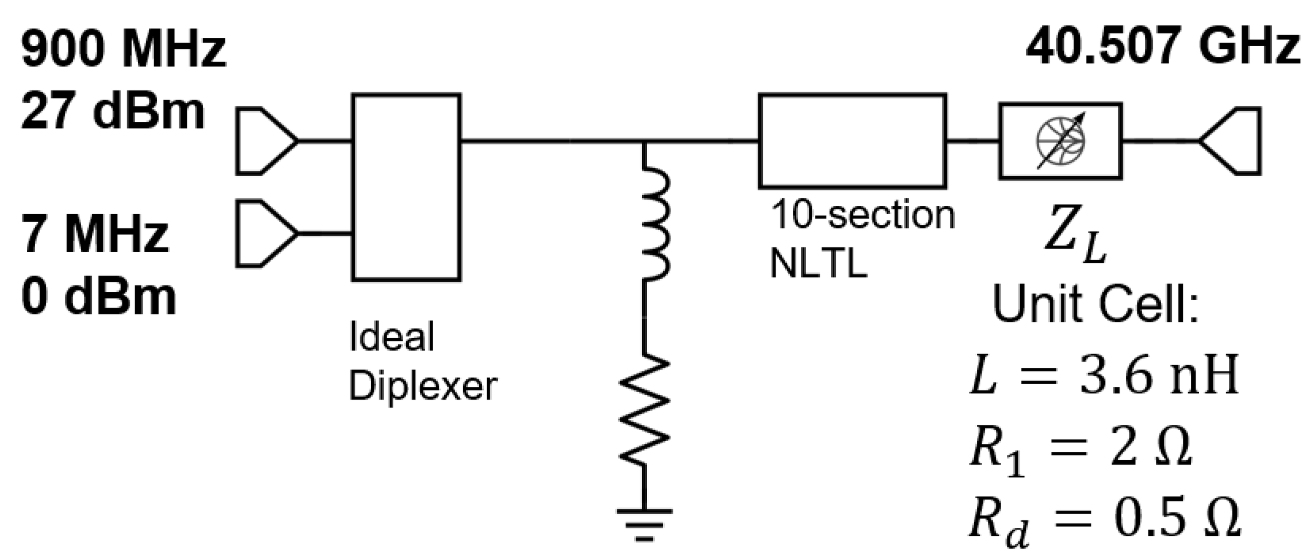

Figure 2: Block diagram depicting means of obtaining required RF fine-controlled frequency – NLTL acts as a subharmonic mixer, multiplying the high power 900 MHz by a moderate factor, then adding a single copy of the DDS output frequency

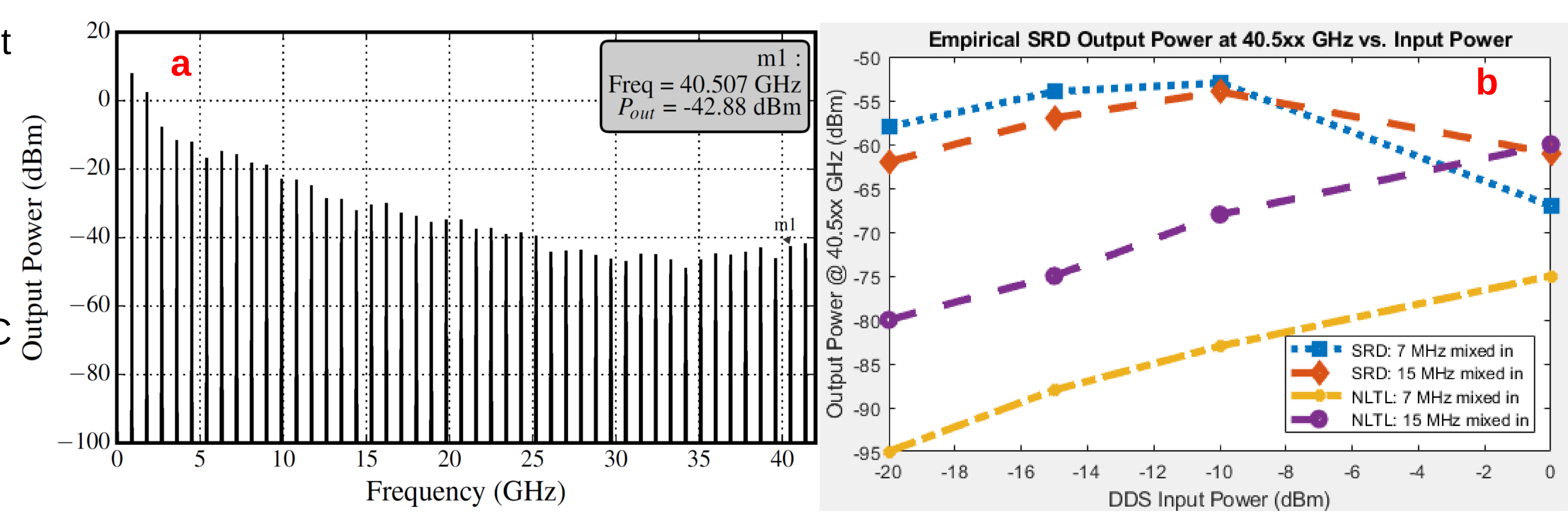

Figure 3: Custom NLTL simulated output power, using load-pull derived ideal output impedance (a) – output power compares favorably to both pre-existing SRD multiplier as well as commercial NLTL (b)

Significance/Benefits to JPL and NASA:

This result demonstrates a relatively simple means of producing highly tunable, spectrally pure millimeter wave signals for use in a wide variety of atomic or molecular spectroscopy applications, while using significantly less DC power than existing solutions. We also have verified the viability of using a flight-qualified FPGA-based DDS to produce the fine-tuning frequency often used in these synthesizer architectures, with sufficiently low noise. DC power reduction for the DDS remains as a future goal.

References:

[1] Toennies et al., 2018 IEEE International Frequency Control Symposium (IFCS). IEEE, 2018.

[2] M. G. Case, "Nonlinear transmission lines for picosecond pulse, impulse and millimeter-wave harmonic generation," thesis

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