II-4. PRACTICAL APPLICATION OF A POSITIVE RESISTANCE UP-CONVERTER FOR ULTRA-LOW-NOISE AMPLIFICATION

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An ultra-low-noise, tunable S-band amplifier which uses a travelling-wave maser (TWM) as the second stage has been developed. The amplifier is made up of a cooled, tunable low-noise S-band varactor up-converter, a fixed-tuned, high-gain, C-band TWM, and an uncooled, tunable varactor down-converter connected in cascade. This receiver configuration has the advantage of combining the large tuning range capability of a parametric up-converter with the ultra-low noise temperature and unconditional stability of a maser.

The practicality of using the low-noise feature of the sum-frequency up-converter had previously not been realized because it is usually a relatively low-gain amplifier whose low-noise performance is degraded by a second-stage noise contribution. In this particular case, however, the second-stage amplifier is a high-gain TWM whose noise contribution is of the order of 1^{o} K. Since the noise contribution due to small maser input line losses is masked out by the up-converter gain, the up-converter and its associated input line are the main sources of amplifier noise. The up-converter exhibits a positive resistance input characteristic, which makes it inherently stable and permits the elimination of the usually troublesome cooled input circulator. The TWM is designed to be unconditionally stable, so that the resultant amplifier exhibits excellent stability characteristics. The varactor down-converter is identical with, and uses the same pump as the up-converter, but has reversed input and output connections. Thus, the resultant tunable output has the same frequency as the system input and is insensitive to pump frequency drift.

The TWM is the principal component in realizing a low-noise system. The maser uses Cr^{3+} doped ruby as the active material and is cooled to 4.2^{o} K during operation. The maser is centered near 6 GHz, and exhibits a gain of about 30 dB and an instantaneous bandwidth of 65 MHz (which determines the overall instantaneous amplifier bandwidth), by using magnetic field staggering techniques.

Two up-converter units have been developed, one centered at 1750 MHz, and the other at 2250 MHz. The output (sum) frequency of both units is set at 6000 MHz (the TWM center frequency) by tuning the converter pump frequency (centered at 4250 and 3750 MHz, respectively) as the input frequency changes. The up-converter uses a balanced configuration (Figure 1) that results in relatively efficient broadband pumping, inherent isolation of signal input and sum output frequencies, and large instantaneous input signal bandwidths. All up-converter development was done at room temperature, and operation of the unit in the $20 - 30^{o}$ K range was achieved by adjusting the bias and pump power applied to the GaAs varactors.

Figure 2 shows the interior details of a breadboard up-converter. Most of the features in the equivalent circuit of Figure 1 are labelled correspondingly in Figure 2. The omissions are: (1) the reduced-height rectangular waveguide at

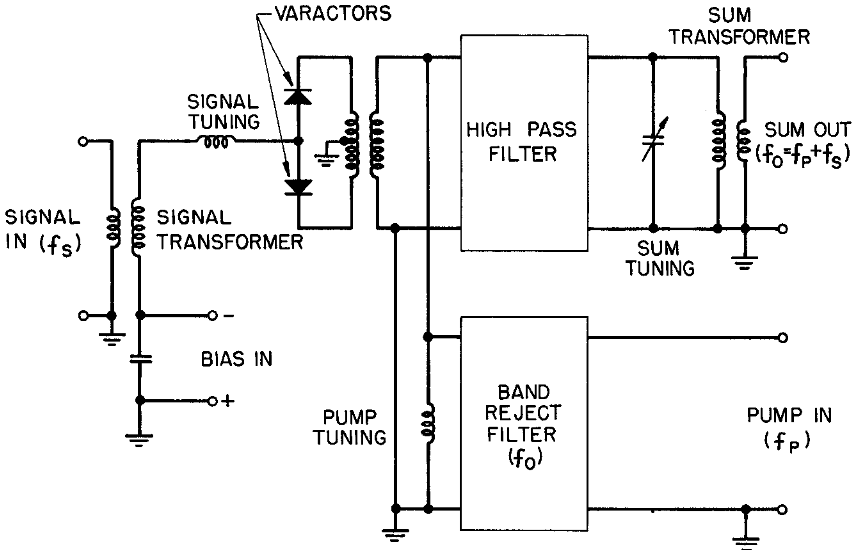

Figure 1. Lumped Equivalent Circuit of Balanced Varactor Up-Converter

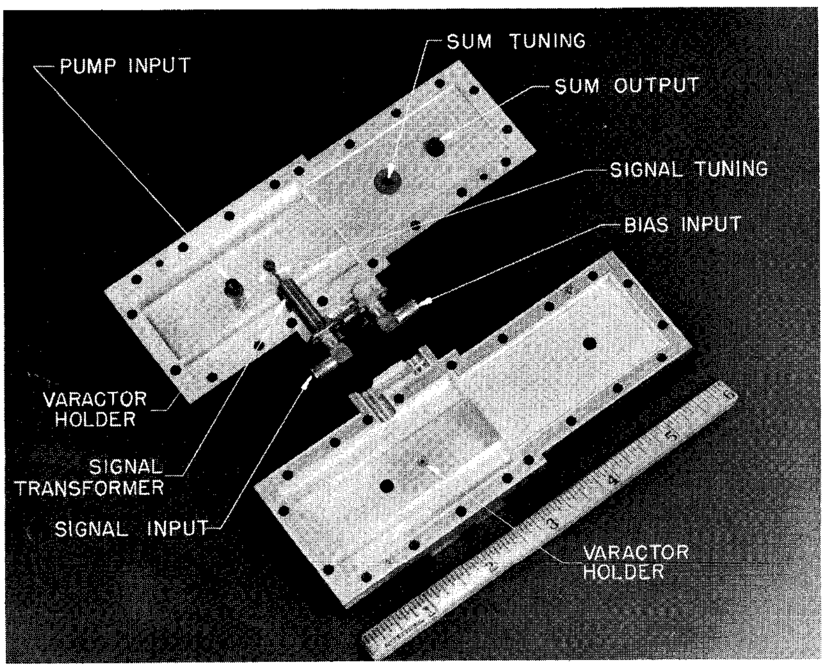

Figure 2. Breadboard Up-Converter

the sum port side of the unit, which acts both as the high-pass filter and sum transformer, (2) the location of the pump port a half-wavelength at the sum frequency from the end wall of the ridge waveguide, which acts as the band-reject filter, and (3) the location of the junction between the ridge and rectangular waveguides, which acts as the pump tuning.

An important design parameter of the up-converter is the signal transformer coupling ratio, which affects the noise temperature, gain, and signal circuit bandwidth (and hence tunability). The theoretical minimum noise temperature of a sum-frequency up-converter with optimum lossless signal circuit coupling is given by:

$$(T_e)_{min} = 2\left(\frac{f_s}{M}\right)\left[\left(1 + \frac{f_s^2}{M^2}\right)^{1/2} + \frac{f_s}{M}\right] T_D \tag{1}$$

where f_s = signal frequency $\approx$ 2 GHz,

M = varactor figure of merit = $(C_1/C_o) f_c$ = varactor nonlinearity x cutoff frequency $\approx$ 30 GHz,

T_D = physical temperature of the varactor.

For M's much greater than f_s, equation (1) becomes:

$$(T_e)_{min} \approx 2\left(\frac{f_s}{M}\right) T_D \approx 0.13\ T_D$$

Therefore, if the diode is cooled to 30^o K, the theoretical minimum up-converter noise temperature is only about 4^o K.

On the other hand, the theoretical maximum gain of an optimally-adjusted sum-frequency up-converter is given by:

$$G_{max} = \frac{\left(\frac{f_o}{f_s}\right)}{\left[\left(1 + \frac{f_s f_o}{M^2}\right)^{1/2} + \frac{(f_s f_o)^{1/2}}{M}\right]^2} \tag{2}$$

where f_o = sum frequency = 6 GHz. For M's much greater than $\sqrt{f_s f_o}$, equation (2) becomes:

$$G_{max} \approx \frac{\left(\frac{f_s}{f_o}\right)}{\left[1 + \frac{2\,(f_s f_o)^{1/2}}{M}\right]}$$

Therefore, for the same numbers as before, $G_{max} \approx 3.9$ dB. In general, however, the signal circuit coupling for maximum gain is different from that for minimum noise temperature. The actual adjustment used favored tunability at a slight cost in noise temperature and a greater cost in gain.

Figure 3 shows the assembly of a breadboard up-converter and maser for preliminary system evaluation of the achievable noise temperature and tunability. Heaters were attached to the up-converter to maintain its temperature at a prescribed value (usually in the range of 15° to 30° K) above the 4.2° K liquid helium bath temperature required for maser operation. A gold-cobalt vs. copper differential thermocouple arrangement was used to read the temperature difference. Figure 4 shows the resultant measured overall noise temperature vs. signal frequency with an up-converter temperature of 32° K and the maser frequency set at 6.0 GHz. Also shown is a dotted curve corrected for the estimated 15° K contribution of the miniature semirigid coaxial input line. In the final system, the use of a large diameter air-dielectric low-loss input line will appreciably reduce this input line contribution. It can be seen that the corrected overall amplifier noise temperature is less than 20° K over a 170-MHz bandwidth and less than 30° K over a 360-MHz bandwidth centered at about 2200 MHz.

It should be emphasized that these measurements are preliminary. Final system performance measurements in a closed-cycle refrigerator will be given. Additional design considerations concerning selection of frequencies to avoid spurious responses, and details of up-converter and down-converter operation will also be covered.

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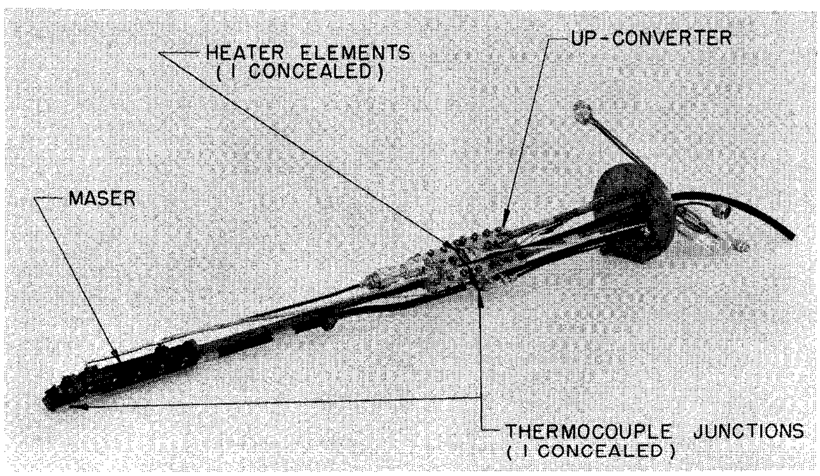

Figure 3. Breadboard Cryogenic Assembly of Up-Converter and Maser

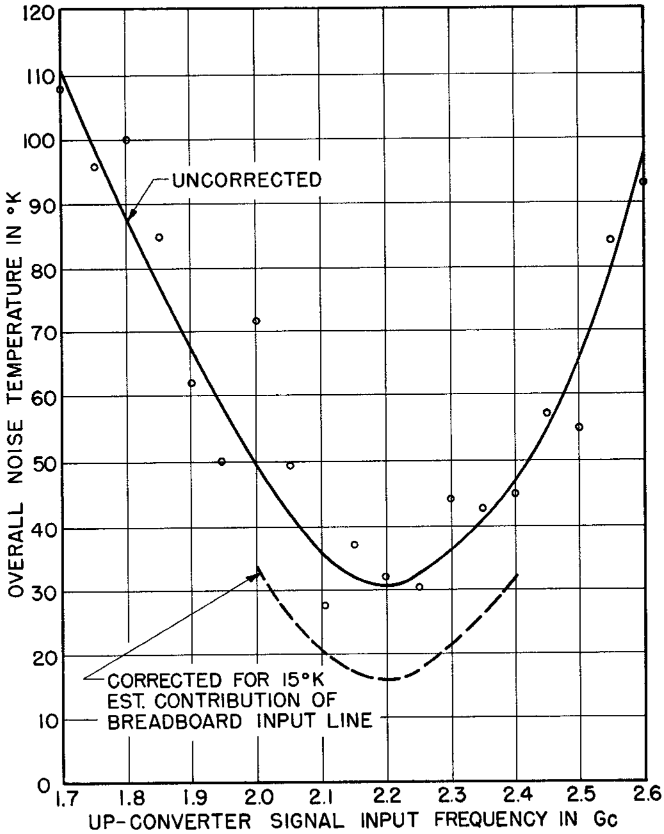

Figure 4. Preliminary Measured Noise Temperature of Breadboard Up-Converter and Maser System vs Signal Frequency (Up-Converter Physical Temperature = 32^{O}K, Maser Frequency = 6.0 Gc)