SOLID-STATE LOCAL OSCILLATOR SOURCES FOR 600-900 GHz

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ABSTRACT

We have developed tunable, solid-state frequency sources covering the 600-720 GHz atmospheric window, and constructed another source for 780-880 GHz which is not yet functional. The sources are intended for use as local oscillators for SIS mixers. The sources are based upon a 120-147 GHz Gunn oscillator, and use crossed-waveguide multipliers for frequency multiplication. The first source, covering the 600-720 GHz window, uses a quintupler; the second, covering most of the 780-900 GHz window, cascades a doubler and a high-frequency tripler. The multipliers use 2T10 Schottky diodes obtained from the University of Virginia Semiconductor Device Laboratory. We discuss the multiplier designs, and report the results of tests of the 600-720 GHz source.

Introduction

With the recent development of sensitive SIS mixers operating in the 600-720 GHz atmospheric window[7, 12, 13], and the prospect of SIS mixers being developed for the last remaining submillimeter window at 780-920 GHz, the development of solid-state tunable local oscillator (LO) sources covering these windows has become important to submillimeter wavelength astronomy. Several commercial vendors offer sources for the 600-720 GHz band[8, 9], but these sources are often expensive and sometimes restricted in bandwidth. As part of the receiver development program for the Submillimeter Array Project, we have chosen to develop our own sources.

The scheme we have chosen to cover these frequency bands uses a Gunn oscillator obtained from J. E. Carlstrom Co.[2] which operates from 117-147 GHz with approximately 35 mW of output power. The cutoff at 147 GHz is determined by the WR-8 output waveguide. Tests have shown that this oscillator can readily be phase-locked throughout its operating band.

For the 600-720 GHz band the Gunn oscillator is followed by a quintupler of our design, built by Custom Microwave[4]. For the 780-900 GHz band we use a doubler purchased from Millitech[8] to generate radiation between 260 and 294

GHz, which then drives a tripler. The Millitech doubler generates about 2 mW of output power in the required range. With a cascaded tripler, it is possible to obtain radiation from 780 to 882 GHz. The tripler was built to our design by Custom Microwave.

High efficiencies for both triplers and quintuplers have been obtained in low frequency multipliers. A quintupler obtained peak efficiency of 4% at 168 GHz with efficiency greater than 1.5% from 165-170 GHz[15]. A tripler obtained peak efficiency of 28% at 107 GHz and greater than 10% efficiency from 100-115 GHz[14]. As these citations illustrate, published work has often concentrated on obtaining very high efficiencies, usually over narrow bandwidths and through the use of resonant structures that are difficult to fabricate at high frequencies. More useful for astronomical purposes, because the power requirements of SIS mixers are relatively low, are broadband multipliers with rather lower efficiencies. An example of a tripler which achieved broadband performance is that of Archer[1], which obtained 3% efficiency over 200-290 GHz. However, Archer's design would be very difficult to scale to high frequencies.

The power required from an SIS mixer local oscillator source can be calculated from the fact that conversion on the first photon peak below the gap varies roughly like $J_1(eV_{LO}/h\nu)$[11]. Thus conversion is maximized when:

$$P_{LO} \approx 0.6 \times \frac{(h\nu/e)^2}{R_{junction}}$$

where $R_{junction}$ is the RF impedance the detector presents at the frequency ν. For typical receivers with $R_{junction} = 25\ \Omega$, and adding a factor of 3 for optical coupling losses and a safety margin, this formula leads to optimal LO source powers of 0.5-1.0 μW for the 600-900 GHz frequency band. To achieve a minimum source output power of 1 μW with our scheme, efficiencies greater than 0.004% for the quintupler and 0.05% for the tripler are required. These efficiencies should be well within the capabilities of current multiplier diode technology. In fact, a multiplication efficiency of 0.003% has been obtained for 7th and 8th harmonic radiation at 800 GHz in a multiplier that was far from optimized for this frequency[10]. Thus, there is good reason to believe that output power levels well above the level needed to drive SIS mixers can be readily generated.

The high-frequency multipliers use 2T10 GaAs Schottky varactor diodes fabricated at the University of Virginia Semiconductor Device Laboratory. These diodes are identical in design to the earlier 2T2 diodes, which are the most successful submillimeter multiplier diodes yet made[3]. These diodes have a cutoff frequency of 4.8 THz; experience suggests that Schottky varactor diodes can multiply effectively up to about one-fifth the cutoff frequency[3], so it is reasonable to suppose that the 2T10 diodes can provide useable amounts of power through 900 GHz.

Design

Figure 1 illustrates the design of the 600-720 GHz quintupler; the design of the 780-900 GHz tripler follows similar principles.

The input waveguide is WR-8, chosen to match the Gunn oscillator. A non-contacting backshort is used in the input guide. A post of diameter approximately one-fifth the waveguide width extends into the middle of the guide. At DC the post is isolated from the multiplier body, because it carries the DC bias to the multiplier diode. At RF, an effective short is produced at the waveguide wall by a $\lambda/2$ transmission line (1.14 mm in length) terminated in an RF short by a parallel-plate capacitor defined with a 25 μm Mylar sheet.

At the end of the post is mounted the whisker. We use a 25 μm diameter, 78% Au and 22% Ni whisker, and etch it to the proper length and point it in a tenth-normal solution of HCl. The whisker forms a transmission line between the input and output guides, which is intended to act as a low-pass filter. At the multiplier output frequency, the coaxial section between the guides is a quarter wavelength; this forms a low-impedance section; the length of the whisker in the input and output guides is approximately a quarter wavelength, and these form high-impedance sections of a blocking filter for the RF. The post in the input guide may also be considered a low-impedance section of this line. Unfortunately, the impedance ratio between the low- and high-impedance sections is only about 1:2, and so the filter is of limited effectiveness. However, this structure is simple and easily fabricated at high frequencies; it is difficult to fabricate more effective structures by mechanical means. (Planar diodes may ultimate allow good high-frequency filters to be built.)

The output waveguide is chosen to be just small enough to cutoff the 4th harmonic radiation when operated at its highest useful astronomical frequency, 720 GHz. The nominal cutoff frequency is 579 GHz. The output waveguide uses a contacting backshort.

The 2T10 diode chip was quartered, forming individual chips in the shape of cubes 100 μm on a side. Each chip is soldered to the top of a gold-plated brass mounting post 190 μm in diameter. The diode post is moved by a differential screw approximately 58 μm per revolution. Contact is made with the diode partially in the waveguide.

In general, one desires highly inductive embedding impedances for the diode at the idler frequencies, that is, the frequencies of the lower harmonics. The main source of inductance in our design is that introduced by the waveguide below cutoff; a secondary source is the inductance of the whisker. This method works fairly well at providing good idler impedances in the tripler, but cannot work well in the quintupler. The impedance associated with the waveguide is highly inductive just below cutoff and decreasingly inductive as the frequency

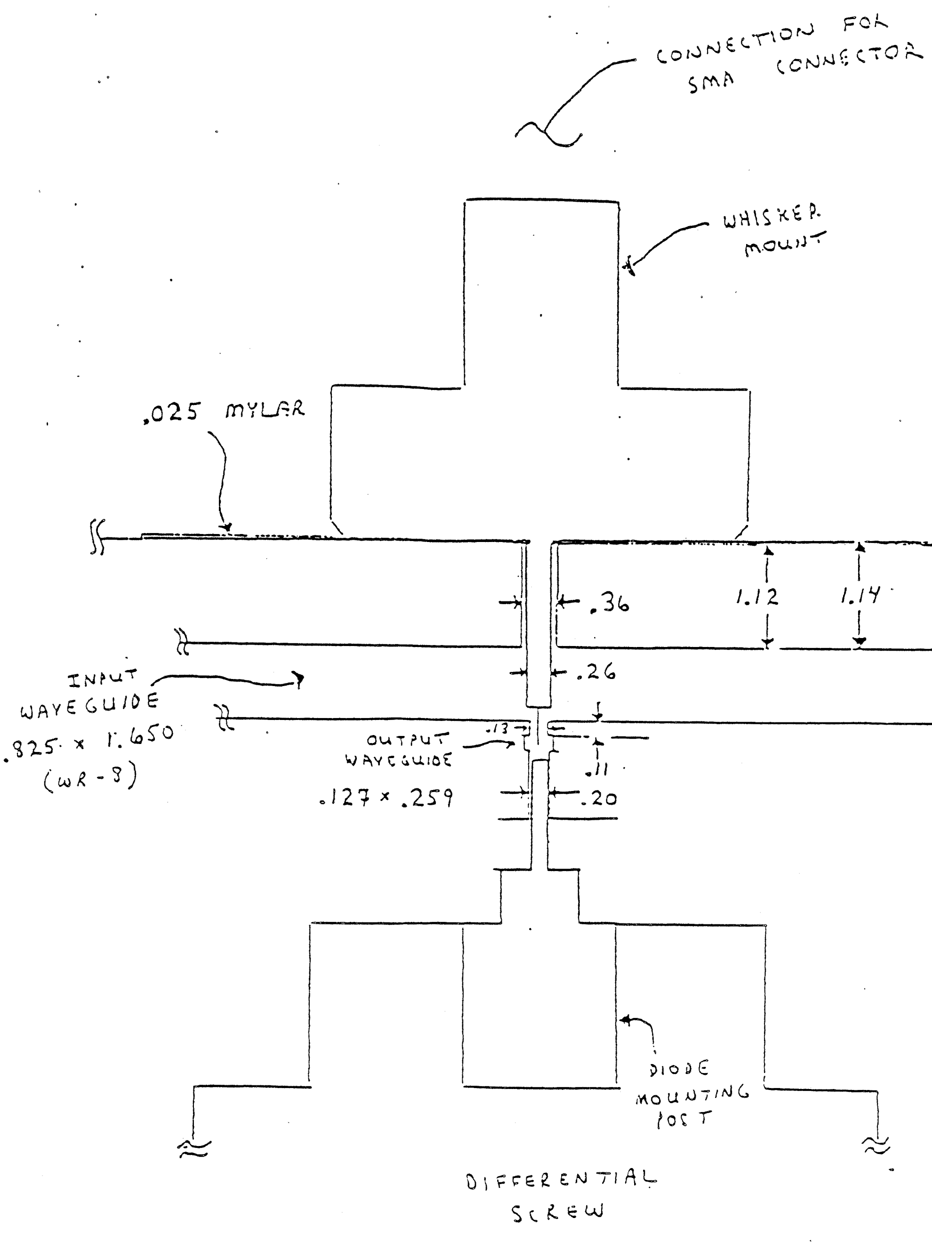

Figure 1: Layout and dimensions of the quintupler for 600-720 GHz. The dimensions are in millimeters.

is decreased. If the 4th harmonic is cutoff in the guide, then this leads to only mildly inductive terminations at the 2nd and 3rd harmonics. The whisker, too, introduces a reactance which increases with frequency. For this reason it is much harder to obtain theoretically optimal efficiencies from a quintupler than from a tripler.

A length of 2.21 mm of output waveguide lies between the multiplier diode and the beginning of the output horn; this length is necessary to adequately suppress both higher-order waveguide modes and evanescent modes from the lower harmonics. The horn is a pyramidal horn with apertures 1.88 mm and 2.72 mm and an axial length of 7.32 mm. These parameters give a gain of 23.5 dB.

Measurements

We have tested the 600-720 GHz source in two ways: measuring the total power radiated with an InSb bolometer system, and measuring the output spectrum to check for harmonic content using a Fourier Transform Spectrometer. Additional tests await the construction of an SIS mixer for these frequencies.

Output Power

The output power was measured using an InSb bolometer system purchased from Infrared Laboratories[5]. The bolometer was calibrated against a narrow-band, fixed-tuned 690 GHz source purchased from Radiometer Physics, which was in turn calibrated against a TK TeraHertz Absolute Power Meter System[6], and shown to produce about 80 μW. The principal uncertainty in the power calibration is the estimate of the relative optical coupling of the two multipliers to the bolometer. Fortunately, the two multipliers have approximately the same gain. Although the Radiometer Physics multiplier uses a dual-mode conical horn while our multiplier use a pyramidal horn, the two horns have approximately the same slant length and aperture size. Thus, coupling coefficients are similar and should not introduce an uncertainty exceeding a factor of two.

The results of the output power measurements are summarized in Figure 2. The output power is in excess of 3 μW from 615 to 720 GHz, except at 630 GHz where an atmospheric absorption line is responsible for the reduced power detected at the bolometer. This power level is more than adequate to drive a well-designed SIS mixer.

There are several causes for the fluctuations in the recorded output power. Broadly speaking, the output power follows the pattern of atmospheric transmissivity; at 630 and 730 GHz, atmospheric absorption lines reduce the signal reaching the bolometer. From 600-610 GHz, output power is disappointingly

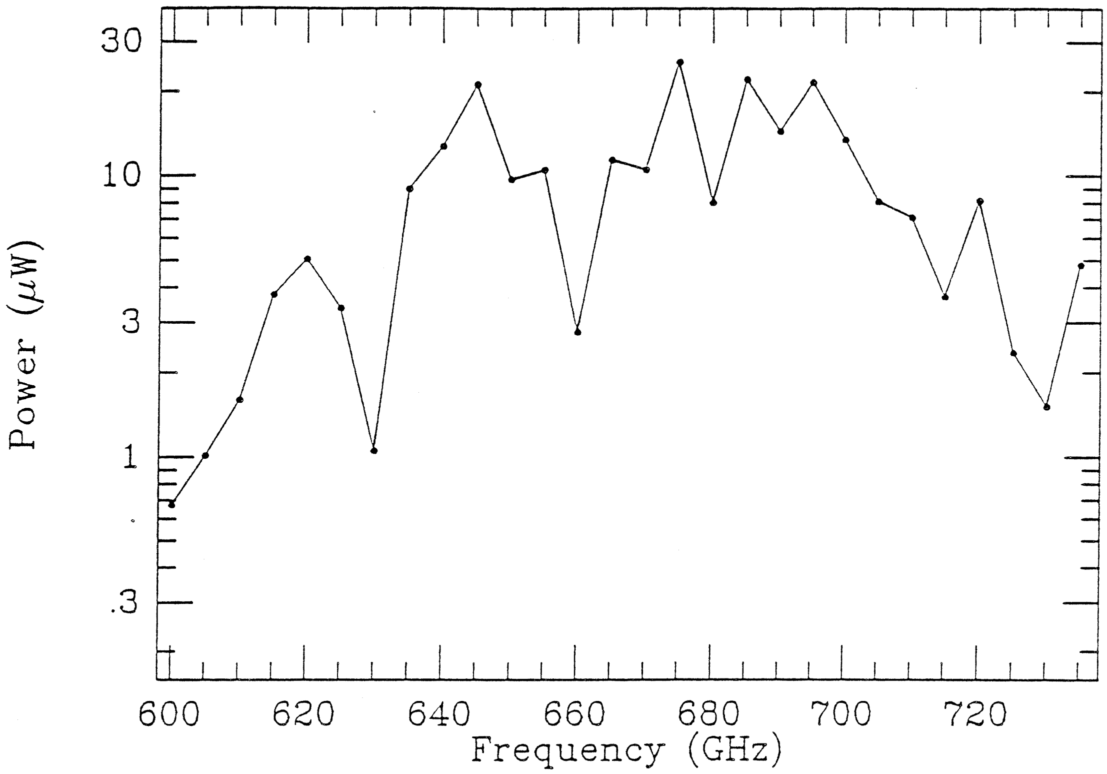

Figure 2: Output power as a function of frequency from the 600-720 GHz source.

low. This we attribute to the operation very close to the cutoff frequency of the guide (nominal cutoff frequency is 579 GHz), so that attenuation is high, and the embedding impedance seen by the diode is likely to be unusual. The cutoff frequency was chosen to be high so as to cutoff the 4th harmonic when the multiplier is radiating its 5th harmonic at 720 GHz. Two considerations — that no 4th harmonic radiation is seen even when the 5th harmonic is generated at 735 GHz, and that the output power should be so small at 600 GHz — both suggest that the output waveguide was built slightly smaller than its nominal design size.

At 660 and 715 GHz, the multiplication efficiency remains high, and the dips in output power are caused by reductions in the amount of Gunn oscillator radiation being coupled into the multiplier diode. The cause of these resonances is unclear. Finally, other variations, such as the dip in output power at 680 GHz inbetween strong signals at 675 and 685 GHz, largely reflect variations in the effectiveness of the tuning backshort in the output waveguide. At 675 and 685 GHz, this backshort has a strong effect, and tunes through a sharp resonance at which output rises dramatically from about 10 μW to over 25 μW. At 680 GHz the performance is nearly the same at most backshort positions, but the resonance is absent. At 680 GHz there is less than a factor of two between the output power at the best backshort position and the output power at the worst. This mediocre performance is probably unavoidable with the contacting backshort design we used in the output guide, and in future we expect to use a non-contacting backshort, despite its added cost and fabrication difficulty.

Output Spectra

The Fourier Transform Spectrometer (FTS) used to observe the harmonic content of the multiplier was built by the Submillimeter Receiver Laboratory of the Smithsonian Astrophysical Observatory for tests of the optical properties of submillimeter materials and other laboratory measurements. It is quite sensitive, and signal-to-noise ratios of 50 dB were commonly achieved with the 600-720 GHz source.

Figure 3 shows spectra taken every 10 GHz from 600 to 720 GHz of the multiplier output. In these measurements the Gunn oscillator was free-running and the frequency numbers reflect the Gunn tuning values provided by the J. E. Carlstrom Co. Coupling between the multiplier and the Gunn oscillator was present — no isolator was used between the two devices — and this may account for the slight difference in frequency between the manufacturer's tuning values and the observed output frequency.

The FTS resolution was 18 GHz and the spacing of individual bins in Figure 3 is 7 GHz, so that unresolved lines are 2.5 bins wide. The free-running drifts of the Gunn are responsible for the line wings resolved in some frequencies at power levels of about -40 dB.

For a clearer view of typical spectra, Figure 4 shows an expanded view of the spectra for the astronomically important frequencies of 650 and 690 GHz. As these spectra show, it is not uncommon to see 6th harmonic radiation. Aside from 600 GHz, where the 5th harmonic radiation is heavily attenuated and 6th harmonic radiation at 720 GHz actually dominates at some backshort settings (with output power of almost a microwatt), the largest observed output of 6th harmonic radiation was at 780 GHz with the source tuned to 650 GHz. However, even at this worst case, the 6th harmonic is 20 dB lower than the 5th harmonic, which, when combined with suppression in receiver optics, would cause negligible contamination in astronomical receivers. More typically the 6th harmonic is 40 dB lower than the 5th harmonic. Also, backshort and bias voltage settings can be chosen to reduce the 6th harmonic output. Moreover, the 6th harmonic is

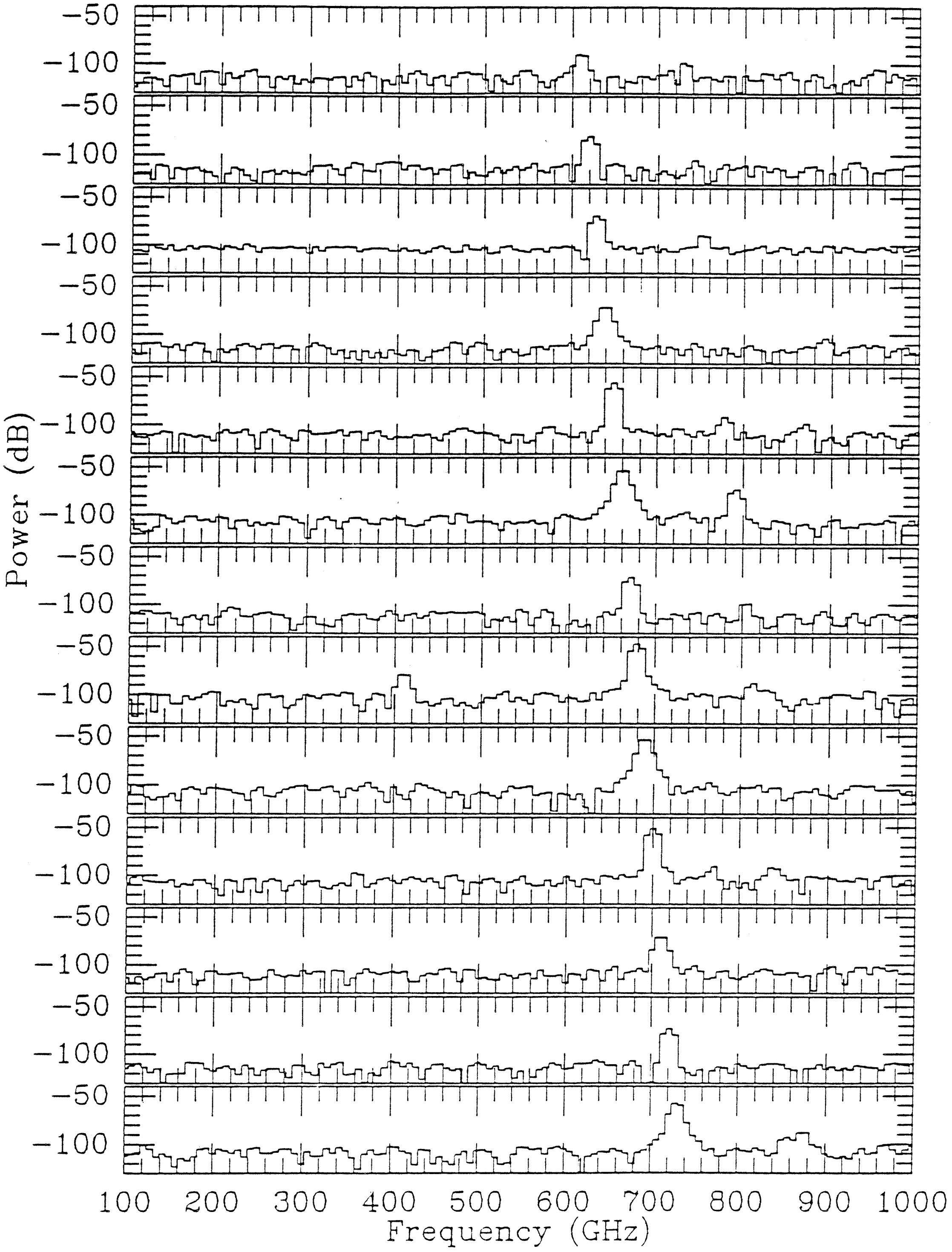

Figure 3: Spectra of the 600-720 GHz source, tuned to nominal frequencies of 600 GHz (top), 610 GHz (second panel), etc., through 720 GHz (bottom panel).

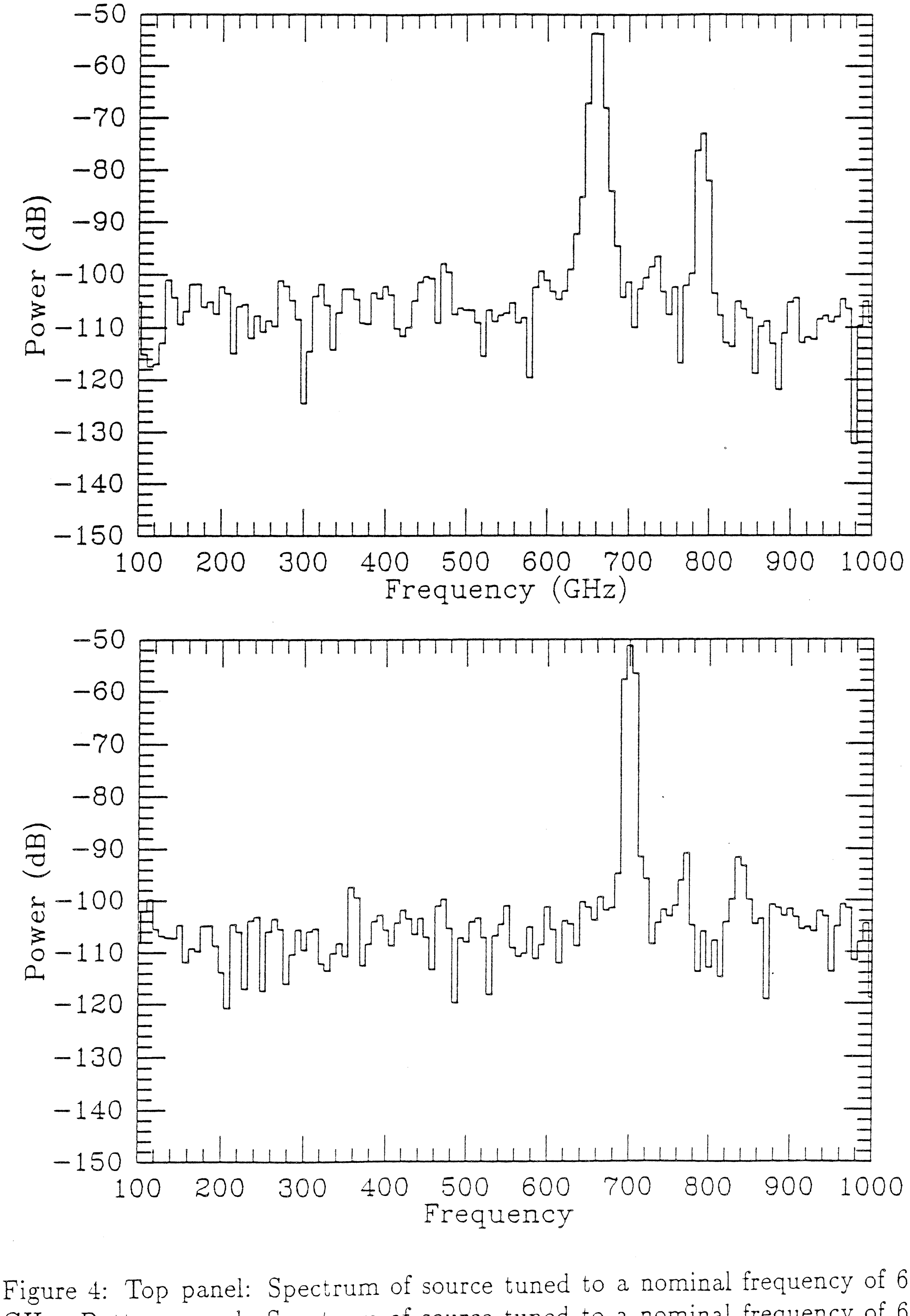

Figure 4: Top panel: Spectrum of source tuned to a nominal frequency of 650 GHz. Bottom panel: Spectrum of source tuned to a nominal frequency of 690 GHz.

suppressed much more rapidly than the 5th as the output power is reduced from the 20 μW level used in this measurement to the 1 μW level that would be used in an actual receiver. For these reasons, we are satisfied that there is no problem with contamination by higher harmonics from this source.

Nor is contamination by lower harmonics a problem. The only spectrum in which lower harmonics was detected is the 670 GHz spectrum, in which 3rd harmonic radiation appeared at a power level down by more than 30 dB from the 5th harmonic power. However, this level is inconsistent with the 3rd harmonic power level expected in the diode, considering the 60 dB suppression that the output waveguide contributes to this evanescent mode. It is conceivable that some power may be leaking out through the input guide or the diode post channel.

Possible Design Improvements

There are several ways in which the design of the high-frequency multipliers could be improved. One especially unsatisfactory feature of the quintupler was the poor performance of its output backshort, suggestive of a poor reflection coefficient. A non-contacting backshort design, though more difficult to fabricate, would be likely to significantly improve the multiplier performance.

A change with uncertain but potentially significant benefits would be to use a resonant blocking filter on the diode post. The 190 μm diameter diode post slides in a 200 μm hole, and is allowed to contact the sides. If contact is made then no TEM modes can propagate, but the cutoff frequency for higher-order modes is on the order of 300 GHz. Thus terminations at both idler and output frequencies may be affected, and power may leak out this port at the output frequency. Use of a proper blocking filter might improve the coupling to the output waveguide mode. In our design no resonant filters were inserted so that diodes and diode posts would be interchangeable between the two multipliers; however, this convenience saves only a modest expense in spare diodes.

It does seem that the output waveguide of the quintupler was slightly too small, making its use from 600-610 GHz problematic. Judging from the lack of 4th harmonic contamination at 735 GHz, a slightly larger waveguide size would allow operation throughout the 600-720 GHz atmospheric window.

As yet we have not investigated the dependence of performance on whisker length, which in our design also changes the location of the diode in the output waveguide. It may be that this parameter is not optimized.

An unclear issue is the cause of the resonances at 660 and 715 GHz, in which less power is coupled into the multiplier diode. It is unclear whether these resonances are a consequence of bad coupling between the input waveguide mode and the coupling post, or a problem with transmission down the whisker transmission line which is terminated by the diode. Probably scale model measurements would be needed to resolve this issue. In any event, it is probably possible to improve the input guide post design.

Conclusion

We have developed an inexpensive solid-state local oscillator source capable of driving an SIS mixer between 610 and 720 GHz. Within that band, the source produces 3 to 50 times (typically 20 times) the power required to drive an SIS mixer. There is still room for improvement in the multiplier design, and this suggests that available Schottky diodes are capable of producing sufficient LO power for SIS mixers at still higher frequencies — very likely through the highest frequencies at which the atmosphere is still transmissive, about 900 GHz.

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