A Submillimeter Tripler Using a Quasi–Waveguide Structure

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Abstract

A new type of frequency multiplier structure is being developed which is suitable for application at frequencies above 1 THz. This structure preserves some of the properties of waveguide for mode control, yet is not truly single mode. The device resembles a sectoral horn, with a varactor diode mounted near the throat. Input and output coupling are through the same aperture, requiring a quasi–optical diplexer. Initial tests are directed at building a tripler at 500 GHz, for comparison with waveguide structures. The diplexer is a blazed diffraction grating with appropriate focusing optics. Model studies show that the impedance match to a varactor should be good, and initial tests of the beam patterns of the prototype indicate that optical coupling efficiency should be very high. The structure also has the potential for use as a fundamental mixer, or as a third harmonic mixer.

Introduction

As the operating frequencies of receiver systems shift toward ever higher frequencies, it has become apparent that there is no clear upper limit to the application of single mode waveguide [1,2]. However, the machining and assembly problems increase rapidly above ~300 GHz, and it seems clear that by some frequency of ~1THz, the cost of waveguide components will be too high for use in most systems. This limitation is purely a practical one; the loss of waveguide does not seem to be a serious limit since submillimeter parts use very short waveguide runs. However, the loss is high enough to be of some concern. Cube corner mixers have been used in the higher frequency range, but suffer from a low beam efficiency and a rather high embedding impedance. This paper suggests a new type of mounting structure to replace waveguide at these frequencies, which combines some of the advantages of both waveguide and quasi–optical structures.

An ideal mounting structure for a >1THz multiplier should have the following characteristics:

1. Ease of fabrication, both in the machining and the assembly with the diode.
2. Good mode control at all frequencies involved.
3. Resistive losses should be low.
4. Impedance level should match varactors, which tend to have a low real part and require series inductance for matching.
5. The structure should be readily suited for whisker contacted diodes. Shape or size of the chip should not be critical, and whiskers should not be too short.
6. If the device is optically coupled, the ports should be linearly polarized.
7. Beamwidth should be reasonably narrow to ease the design of coupling optics.

The structure being studied appears capable of satisfying all of these points, although tests are still in progress. The relative ease of fabrication of the 500 GHz prototype indicates that a scaled device at well over 1 THz should be practical. Additionally the needed coupling optics have been developed, which appear capable of separating the input and output beams with low loss as well as coupling them to a source and load.

Quasi–waveguide Mount

The structure as shown in Fig. 1, is essentially a pair of parallel metal plates separated by less than $\lambda/2$ at the highest frequency of interest, with two intersecting sidewalls to guide the beam. The sidewalls intersect at 90° in the prototype, although other angles may be equally good or better. The varactor is mounted between the top and bottom plates, spaced from the vertex by less then 0.71λ at the highest frequency. With these constraints, the structure can couple only to a mode with the electric field uniform and perpendicular to the plates, and the mode pattern in the H plane has single maximum. To produce a convenient output beamwidth, the top and bottom plates are made nonparallel so that the separation becomes a few wavelengths at the opening. The best situation for ease of design would be to make the planes parallel at the diode, and then change the angle to begin the flare, as in a typical waveguide–horn interface. However, this makes the structure impractical to build at >1THz, so the approach taken was to maintain a continuous flare, which is slow enough to not greatly perturb the embedding conditions at the diode. If this flare becomes too fast, the embedding impedances may change and the evanescent higher modes at the diode are not sufficiently cut off before the separation becomes great enough for them to propagate. The relatively large spacing of the plates (compared to reduced height waveguide) makes mounting a diode and whisker easier, and reduces the losses. The wide side wall spacing minimizes their contribution to the loss except near the vertex.

A model study was done to determine the embedding impedances in this structure. A coaxial probe was introduced up to the effective terminal where the diode would be contacted, and a "contact whisker" of various lengths and shapes extended to the opposite wall. Various vertex distances within the constraint of the maximum spacing were also tested. The general result is that any antenna within this structure acts as an inefficient radiator so that it maintains the character of a lossy transmission line, with the loss increasing with frequency. Thus it shows resonant behavior, which is pronounced when the plate spacing is as wide as used here. The diode terminal impedance circles the Smith chart, at a high value of ρ, with approximately periodic behavior dependent on the physical length of the whisker, rather than the plate spacing. The match initially appears quite poor at all but the highest frequencies, but it is found that through the choice of whisker length and shape, it is possible to achieve a considerable range of impedances at three harmonically related frequencies. By adding a short circuited transmission line in series with the contact whisker (with two adjustable parameters, length and impedance), it is possible to produce an even wider range of values. The net result is that a reasonable match may be made to the impedance of a varactor, over a bandwidth of 5%, at all three frequencies required for a tripler, including a low resistance at the idler. The best configuration occurs with the

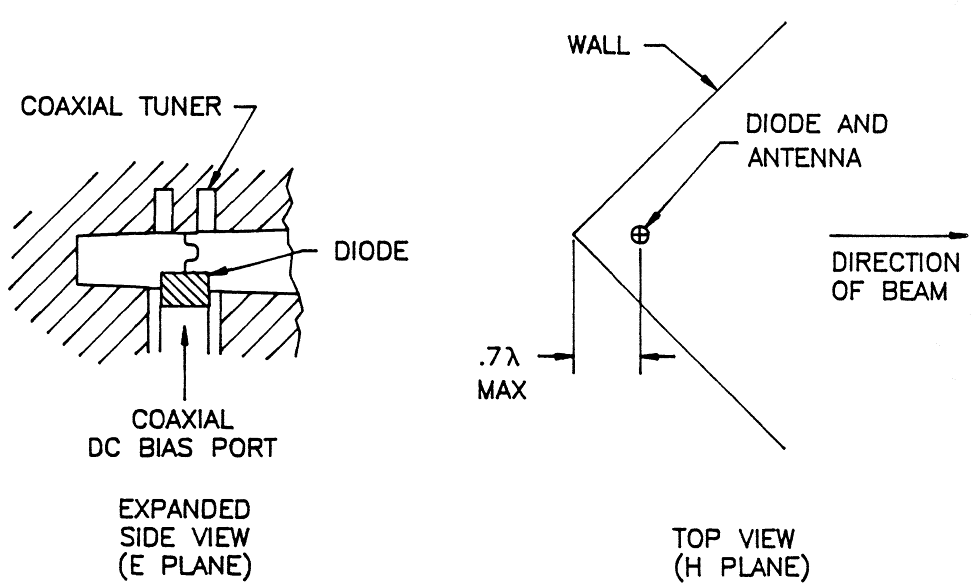

Fig. 1. Top view and side view cross section of the quasi–waveguide tripler.

maximum plate separation and vertex distance allowable, but there is still some freedom in the choice of whisker parameters (length, diameter and shape). No other flare angles were tested, so this remains as another possible adjustment. While the bandwidth of this particular choice of geometry is limited, it seems good enough to evaluate the potential of the device.

Based on this design, a prototype tripler has been fabricated for an output frequency of 500 GHz. Initial tests seemed best at a frequency where comparison with the results for waveguide mounted devices is possible, while this frequency is high enough to permit a realistic assessment of the fabrication difficulties. The structure is built as a split block, with the bottom plane and side walls in one part, and a flat plate forming the other half. The diode in this device is biased through a coaxial filter designed to present a short circuit at all three frequencies involved. As in typical mixers and multipliers, the diode chip is mounted on the end of the coaxial filter, forming much of the final section. The diode chosen is U.Va. type 2T2 with $C_j(0) = 6fF$, $R_s = 12\Omega$, and $V_b = 11V$. The flare angle of the plates is 9°, over a total length of 2.3 cm, so that the opening aperture is 3.6 mm. The whisker is mounted on the end of a short circuited coaxial section providing the needed reactances at the input and output.

While the bottom half of the mount was made by electroforming over the corner of a cube, it could also easily be machined, except for the vertex itself, where a small radius has little effect. Probably the most difficult machining area is in the coaxial bias filter, which would be impractical at substantially higher frequencies. An alternative is to use a very thin capacitor for rf bypass between the diode and the bottom plane; this would also require a thin diode. A bias wire can then connect to a feedthrough at the vertex.

Coupling Optics and Diplexer

A quasi–optical device is only of value if it can be coupled efficiently with optics. In this case the input power is likely to be derived from a waveguide mounted varactor multiplier with a feed horn on the output, which may be approximated by a Gaussian beam waist. The output load will almost certainly be an antenna coupled mixer but the details of the pattern of such a mixer are presently unknown. We can only assume that a Gaussian beam is suitable.

Beam patterns for this device are expected to be those of a uniformly illuminated aperture in the E plane and one sector of that due to a square array of four antennas in the H plane. The E plane pattern has a moderate sidelobe level reducing its coupling efficiency to about 85% to a Gaussian mode, while the H plane pattern is well tapered with no sidelobes, and thus couples with high efficiency. The beam is unusual in that the phase centers for the two planes are far apart. The H plane originates essentially at the vertex, while the E plane center is at the physical aperture. Thus the optics must be very astigmatic. In addition, the beams at the input and output are very different in size, particularly in the E plane.

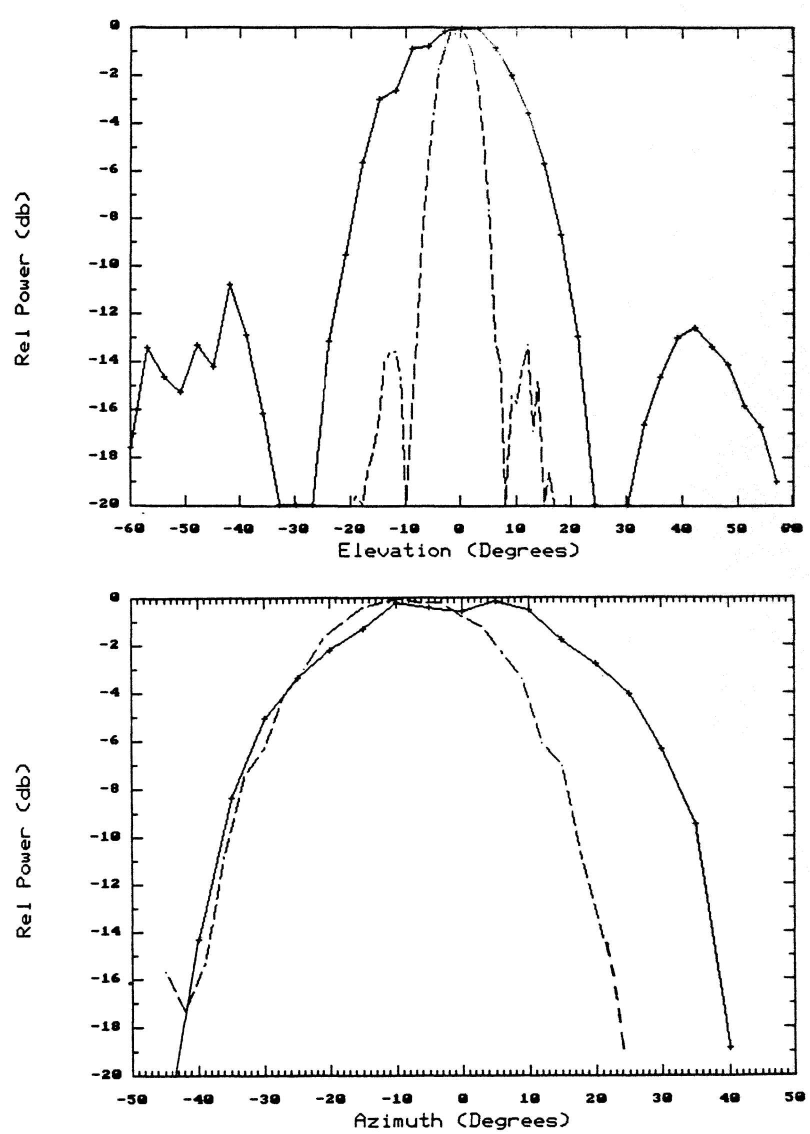

Fig. 2. Cuts through the principle planes of the beams in the E plane (azimuth) and the H plane (elevation). Solid line is at 164 GHz, dashed line is at 492 GHz. Beams are for the tripler without additional optics.

Tests have been performed using the varactor diode as a video detector at both frequencies, with sources at 164 GHz using a doubled Gunn oscillator, and at 492 GHz using the same oscillator multiplied by six. E and H plane cuts are shown for the prototype in Fig. 2, for both frequencies of interest. Full contour maps show no additional features out of the principle planes. These patterns confirm the theoretical predictions, but the H plane at the output frequency is off center by about 9°. This is due to a small asymmetry in the whisker location or shape, but otherwise the beam shape is as expected.

Frequency separation in the submillimeter may be done in several ways, but is particularly easy for a tripler because of the large frequency ratio. While a perforated plate high pass filter would work well [3], an easier device to fabricate is a diffraction grating. With the correct grating period, the input frequency can be below the onset of diffraction so that the grating behaves as a simple mirror, while the output can be scattered in a very different direction in the first order. A particular advantage of this mode of operation is that the input signal is well isolated from the output, which makes measurement of the output power easier since filters are not needed. The efficiency of this scattering can be made very high through the correct choice of reflection geometry and the blaze angle of the grooves. The electric field must be perpendicular to the ruling direction for high efficiency. A convenient configuration is with the grating tilted by 45° relative to the two beams, reflecting the input through 90° and the output by 45°. This requires a blaze angle to the grooves of 22.5° and a period of 0.86 mm. These optics are shown in Fig. 3. There is no

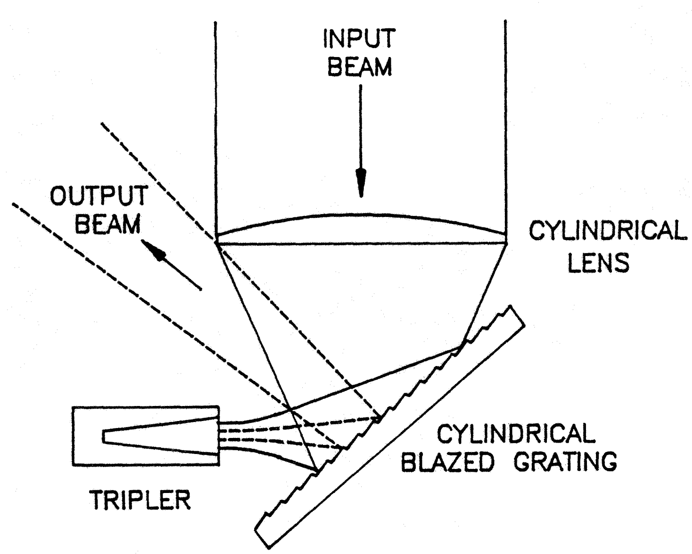

Fig. 3. Diplexer and optics to separate and focus the beams. The grating is cylindrical in the plane out of the figure.

scattering loss at the input, while the theoretical scattering into the two possible unwanted orders at the output totals about 5%. Gratings may be curved in one dimension without loss of function, so a cylindrical grating with a radius of curvature of 5.3 cm is used to eliminate the the very rapid divergence in the H plane. For a highly curved surface such as this one at an off–axis angle, there is higher loss at the edges due to the projected tilt of the grooves relative to the polarization vector.

These optics have been tested with the prototype and show essentially the intended function. The grating efficiency is in fact very high and a scan through two orders shows only 3% of the power in zeroth order relative to the desired first order. The spurious second order is exactly backscattered and is unmeasurable, but is predicted to be the same as the zeroth order. The focusing action is very good in the H plane, producing a beam at the input requiring only one further cylindrical focusing mirror or lens (in the other plane). At the output frequency the beam can be made fairly symmetric with just the one mirror. One additional complication is due to the off axis cylinder; the focal length of such a mirror

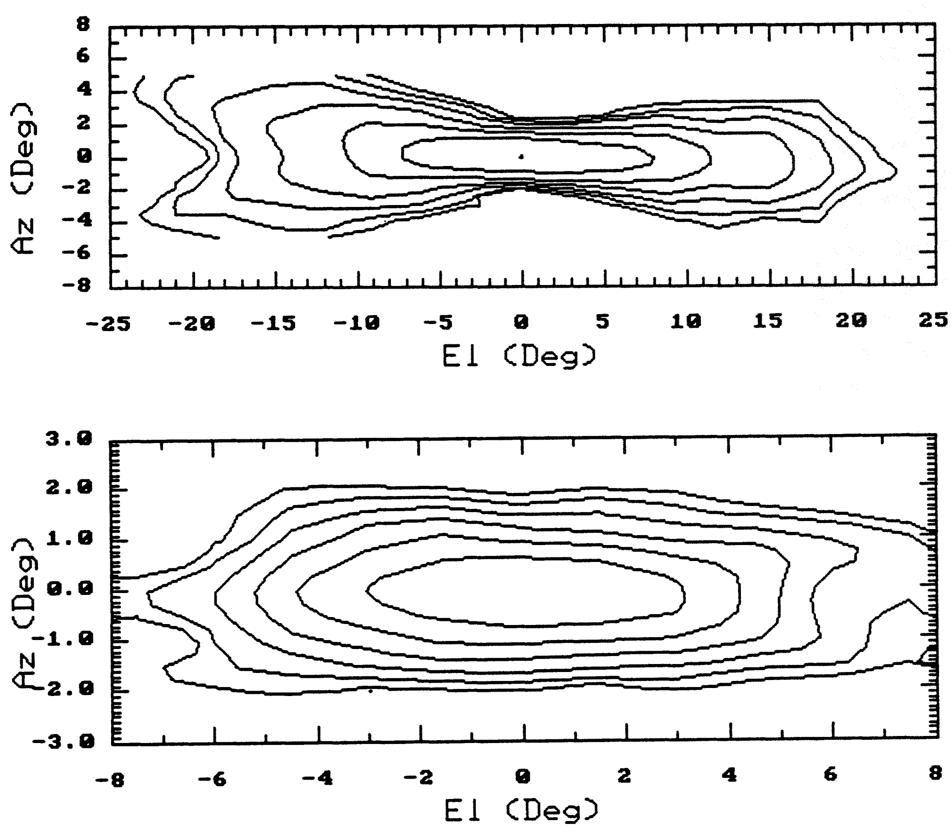

Fig. 4. Beam pattern measured at the line focus of the cylindrical grating at (a) 164 GHz and (b) 492 GHz. Contour interval is 3 dB. The focal distance is different for the two frequencies.

depends on the incidence angle (in the plane of Fig. 3). Because the beams are broad in this dimension, this is quite noticeable in the beam patterns, particularly for the input since this beam is the widest, and the most off–axis. This effect is apparent in the contour map of the input beam, shown in Fig. 4a, as measured near the refocusing point about 50 cm away. The problem is much less apparent in the output beam, shown in Fig. 4b. The easiest cure is to make the grating a different shape, but a periodic ruling can only be made on a few surfaces. It appears that a conical grating can satisfy the requirements, if it represents only a small distortion of a cylinder, but this solution remains to be tested. Optics beyond this point are still being designed, but appear to be straightforward mirrors or lenses.

Conclusions

A new type of mounting structure is proposed for use in a frequency tripler, which is relatively easily fabricated for frequencies above 1 THz. Beam patterns are suitable for efficient coupling to an input source, although the optimum optical system remains to be designed. The present use of a blazed diffraction grating appears to be an excellent means to separate frequencies, with high input–output isolation. The behavior of the device seems less suitable for use as a doubler, although this has not been explored in detail.

A second use might be as a mixer mount for a higher performance submillimeter mixer than cube corner mixers. The application would be much more narrow band, but offers more optimal impedances and a greatly reduced side lobe level. It might also be practical to use for a third harmonic mixer, extending the frequency range of mixers using multiplied sources. A recent analysis of a third harmonic mixer for 1 THz indicates that a properly designed mixer should be quite competitive [4], but this analysis has not been extended to the impedance environment presented by this structure.

References

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