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FREQUENCY MULTIPLIERS FOR EXTENSION OF FREQUENCY RANGE OF MILLIMETER WAVE SYNTHESIZERS

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Abstract

This paper has a deal with the frequency range extension of millimete wave synthesizers (26–118 GHz) through frequency multiplication to provide a reliable, relatively inexpensive, and simple in operation tunable synthesized sources up to submillimeter-wave length band. Frequency doublers and triplers using planar GaAs Schottky barrier diodes as the non-linear element have been developed. Description of their waveguide mounts having no any external tunings and biasing is given. Harmonic generation conversion loss at various frequencies for several practical multiplier assemblies are presented.

Examples of practical application of such source (synthesizer +multiplier) in microwave spectroscopy are demonstrated.

Keywords: Millimeter-wave frequency conversion, multiplying circuits, frequency synthesizers, millimeter-wave spectroscopy.

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1. Introduction

Tunable sources of signal having high stability, spectral purity, and low phase noise are often needed. A quite general practice for this purpose is employing frequency multipliers to generate harmonics of very stable phase-locked microwave sources. Commercial synthesizers, for instance, of Hewlett-Packard cover frequency range up to 50 GHz, and with active frequency multipliers up to 110 GHz (maximum output power is about 1-3 dBm) [1]. Nevertheless there is still a lack of synthesized sources in millimeter- and submillimeter-wave length band having enough power for conventional microwave measurements (sweep generators as reference sources, network analyzer, etc.).

Such radiation sources as sideband generation by mixing of two infrared laser emission (200-3000 GHz) [2], or sources based on Russian BWOs (up to 1200 GHz) [3], which are still out of competition in spectral purity and output power (up to 100 mW below 350 GHz, and about 1÷10 mW at 350-1200 GHz frequency range), are quite expensive and sophisticated in operation. Thus harmonic generators are still in demands to extend the working frequency range of existing commercial synthesizers.

Two types of multiplier mount, doubler and tripler, were designed to extend output frequency range of "Kvarz" synthesizers [4] (output power is 5÷20 mW at 26-118 GHz frequency range) up to 80-270 GHz.

Multiplier constructions are described, conversion losses for each harmonic in the whole frequency range are measured, and examples of observing molecular spectra up to 500 GHz will be shown in Discussion.

2. Frequency Multipliers Design

The design of frequency multiplier was based on an earlier prototype structure, [5], [6]. Resistive principles of harmonics generation with planar Schottky-barrier beam lead diodes as non-linear elements has been used. The resistive diode frequency multipliers are significantly less efficient than the varactor multipliers, [7], [8], (theoretically conversion efficiency of the reactive multiplier could be 100%), limited in output power, but they can be made very broadband, easier to tune (for instance, the varactor multiplier mount [9], has 3 tuning backshorts), there is no need in additional harmonic idlers, have a good coupling between input radiation and the diodes, and they don't demand high power pump source. Furthermore, in millimeter wave lengths the resistive junction of Schottky-barrier diodes provides enough loss to prevent parametric oscillation, i.e. Q-factor of nonlinear element is close to 1, what makes varactors less efficient and gives an advantage to resistive harmonic generators above 100 GHz.

In presented multipliers a full-wave rectifier circuit for 2nd harmonics generation (doubler), and clipping circuit of antiparallel pair of diodes for frequency tripling were employed. The clipping threshold of output waveform in our case was controlled by different forward conduction beginning voltages (0.5 V for silicon, and about 1 V for gallium arsenide).

Gallium arsenide planar Schottky-barrier diodes manufactured by "Salut" Research-Production Enterprise, Nizhny Novgorod, Russia was used. Power tolerance of diodes (3A147A-3, 3A147Г-3) is about 17 dBm, breakdown voltage is 8 V, core symmetry was not worse 5%, junction capacitance and resistance were $C_0 \cong 0.008 \div 0.012$ pF, $R_S \cong 4 \div 10\,\Omega$.

A. Doubler

The mount geometry of frequency doubler shown in Fig. 1 is two block construction split along upper wide wall of input waveguide (e.g., input waveguide - WR-10 at 78-118 GHz).

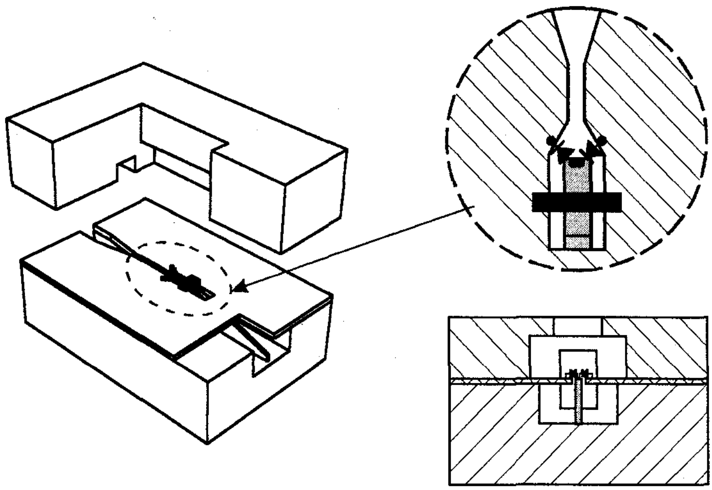

Fig. 1. A detail view of the frequency doubler split along wide wall of input rectangular waveguide; output rectangular waveguide is perpendicular to the input one.

The doubler is comprised of the transmission lines in following order: input rectangular waveguide - complementary finline – uniplanar coplanar waveguide - diode mount - slotline – unilateral finline - output rectangular waveguide (WR-5 at 78-118-GHz) which is perpendicular to the input one.

The slotlines are made from a thin (0.15 mm thickness) metal plate. The coplanar waveguide is formed by plate of the input finline and the output slotline which then narrows to gap of 0.1 mm with characteristic impedance about 50 Ω.

The diodes are placed at the junction of coplanar waveguide and slotline between the end of finline plate and slotline plates.

Closely matched pair of diodes was sort out; there is no bias circuit and diode leads are grounded to provide a minimum of parasitical capacitance. The diodes are placed at $L = \lambda_{2nd}/4$ (λ_{2nd} is the wavelength of output radiation) from the short end of coplanar waveguide. This backshort length is $\lambda_{4th}/2$ for 4th harmonic what strongly reduces its output power generation. Besides balanced circuit properties the fundamental frequency filtering is realized by dimensions (higher cutoff frequency), and orthogonal orientation of input and output waveguides.

There is a hole in the upper part of construction over the diodes to prevent short circuit of the output of the grounded coplanar waveguide, to give access to the diodes, and to permit multiplier frequency range adjustment by changing position of tuning dielectric plates (0.5 × 0.2 × 0.1 mm^3 dimensions with one-side metallization).

B. Tripler

The tripler mount configuration is finline with different dimensions of rectangular input and output waveguides (e.g., WR-10 and WR-5 respectively), and the pair of antiparallel diodes placed at their junction as shown in Fig. 2.

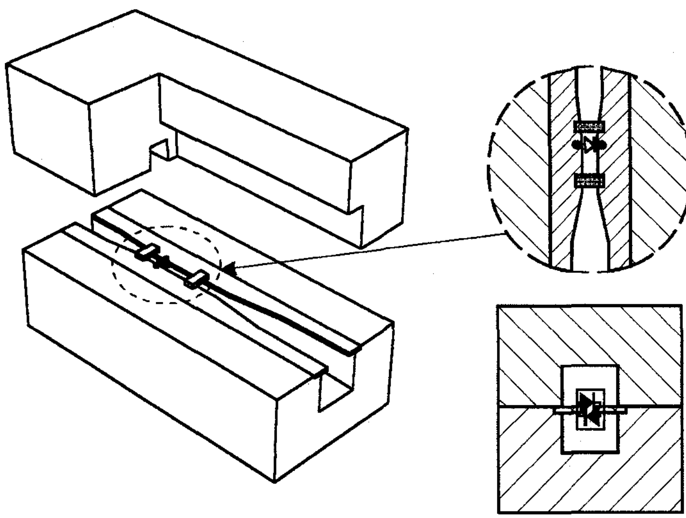

Fig. 2. A view of the tripler block split parallel short wall of waveguides.

The frequency tripler consists of two blocks; splitting plane is parallel to the short waveguide walls. The thin (0.1 mm) metal plate soldered to the one part of construction having an 0.1 mm gap forms finline waveguides. The diodes are mounted at opposite sides of the metal plate of slotline in maximum of electric field at the $\lambda/4$ from the plane of waveguides junction. The diodes have no biasing circuit what simplifies construction and reduces parasitical capacitance.

One side metallized polyamide plate (dimensions of $0.5 \times 0.2 \times 0.05$ mm^3) is placed at the distance of $\lambda_{3d}/4$ from diodes in the input waveguide forming a short circuit for 3rd harmonic. A similar plate is placed after the diodes for output radiation matching. For adjustment of operation frequency range these plates can be moved through the hole (3 mm in diameter) in the upper block of the tripler.

3. Discussion

Let us shortly remind the efficiency limit of frequency conversion loss for resistive frequency multiplication principles. In an ideal (having no any losses) full-wave rectifier circuit n-th harmonic generation efficiency can not exceed $\mathbf{n}^{-2}$ [10] and at least 75% of input power dissipates as dc. For doubling ultimate value of conversion loss is –6 dB, for tripling it is –9.5 dB. For the real diodes having forward voltage resistance it would be –8.8 dB for doubling [11], and about –21 dB for 4th harmonic generation. With increasing of output bandwidth one has to get lower conversion efficiency (e.g., in [12] conversion loss was –13 dB at 66-94 GHz output frequencies). For diode clipper circuit (frequency tripling) predicted by theory conversion loss is about –15 dB while sinewave is clipped at 0.6 of its peak value.

For measurements of multiplier characteristics millimeter-wave synthesizers as pumping sources were used (frequency range was 26÷118 GHz, and 5÷20 mW of output power). No any frequency optimization during the measurements was performed.

The problem of harmonic resolution and its output power measurements was one of the main reason constraining the authors in testing of such multiplier constructions at frequencies higher 150 GHz until the use of spectroscopic technique for millimeter wave power detection [13]. This technique is based on absorption of a radiation in spectral lines of a rarefied gas sample and measuring of its heating by photo–acoustic method. Wells known spectral line parameters provide high frequency resolution in harmonics measurement without any additional filtering.

Measured by this method frequency conversion losses (flange to flange) for several multipliers assemblies are shown in Fig. 3. As one can notice, for tripler T1 (78-160 GHz output frequency) the measured values –13÷20 dB are close to theoretical ones. Maximum output power of about 3 dBm was obtained.

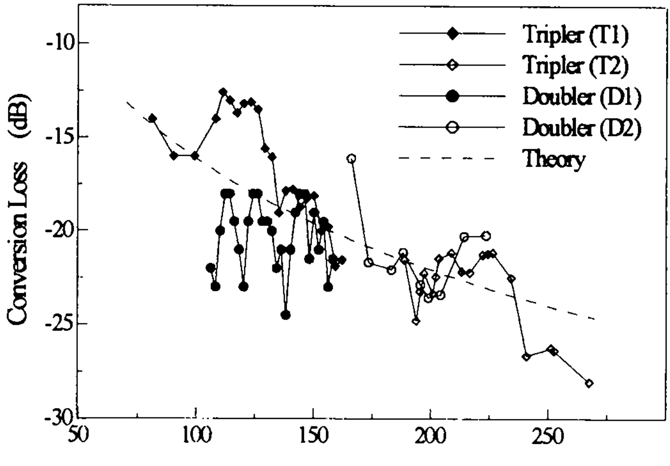

Fig.3. The measured conversion losses of two doublers (D1 - 100÷160 GHz, D2 - 160÷230 GHz), and two triplers (T1 - 78÷160 GHz, T2 - 160÷270 GHz of output frequencies). There was no special tunings and biasing at measurement frequencies. Dash line is well known frequency dependence $L(\omega) = L_0(1 + k\cdot\omega^2)$ for detectors and multipliers.

Input harmonic rejection was more than 20 dB, even harmonic suppressions (relative to power of 3rd harmonic) were about 20 dB for 2nd, and more than 30 dB for 4th ones. Conversion loss for 5th harmonic generation was about –45 dB. Since one of the task of this frequency multiplier design was obtaining of maximal broad working frequency range and output power flatness, so the doubler efficiencies are rather less than it could be in narrow-band device. Output power was not exceed 1 dBm, input harmonic rejection and odd harmonic suppression was not less than 20 dB. A dash line in Fig. 3 depicts common tendency of conversion losses ($L(\omega)$) to frequency (ω) dependence as $L(\omega) = L_0\ (1 + k \cdot \omega^2)$ [14], where k is coefficient determined by shunt capacitances. Increasing of the conversion loss for tripler T2 at frequencies over 270 GHz (–50 dB at 300 GHz), and for 4th harmonic generation of doubler D2 (about –50 dB) was observed. That is because of the tuning elements are suppressing the harmonic output radiation at this frequency range. Moreover, to operate as quadrupler the doubler mount should have another length of input coplanar waveguide L.

The frequency multiplier performance is sensitive to variation of input power, but as can be seen from Fig. 4 the output power of harmonic generation versus input pumping power is about linear function. That is inherent characteristic of resistive frequency multipliers what allows using them for low power primary sources of millimeter wave radiation.

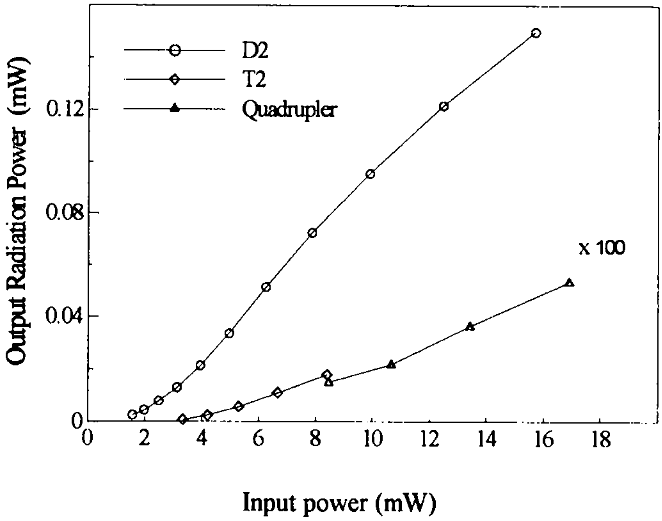

Fig. 4. Conversion loss dependence upon pumping power at 110 GHz input frequency for doubler D2, tripler T2, and quadrupler (D2 was used).

The multiplication technique was early widely used and developed for spectroscopic purposes. For example, Gordy had used 4-16 harmonic of K-band klystron for observing OCS rotational lines [15]. Not claiming to novelty we would like to present application of the multipliers together with "Kvarz" synthesizer [4] in the range of 78-118 GHz as the primary radiation source on conventional absorptive spectrometer at *Laboratoire de Spectroscopie Hertzienne*, University of Lille, France [16]. The spectrometer employs free space absorption cell (2 m long), and cryogenic *InSb* bolometer as millimeter-wave receiver.

The sensitivity of the spectrometer with primary radiation source given in terms of absorption coefficient of spectral line was about 10^{-8} $cm^{-1}\cdot Hz^{-1/2}$. Measured sensitivity of the spectrometer with multipliers is shown in Fig. 5.

The incident radiation was frequency modulated, then the detected by bolometer signal was demodulated by Lock-in amplifier at second harmonic of modulation frequency which results a second derivative lineshape of observed spectral lines. The example of line record at 413 GHz is depicted in the insertion of Fig. 5. The line corresponds to transition $J = 34 \leftarrow 35$ of main isotop of OCS molecule in ground vibrational state, line absorption coefficient is $1.3 \cdot 10^{-3}$ cm^{-1}.

Since strong lines absorption coefficients of majority of molecule species at this frequency range are within $10^{-3} \div 10^{-1}$ cm^{-1}, the employing of the multipliers with only one synthesizer permitted observation of spectral lines in very broad frequency range from 80 GHz to 500 GHz. Detection of spectral lines with known absorption coefficients made possible to measure both the spectrometer sensitivity and frequency multiplier performances itself for high order harmonics with high frequency resolution.

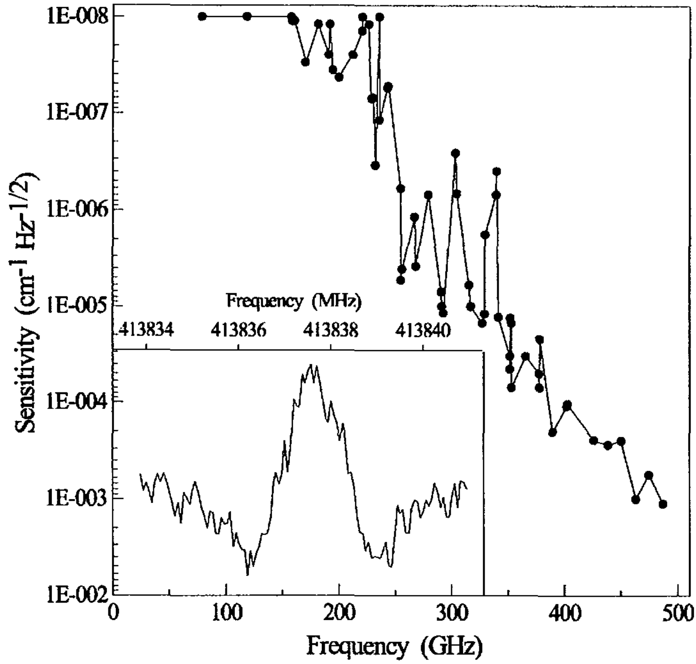

Fig. 5. The spectrometer sensitivities versus frequency; the sensitivity is expressed in units of measurable spectral line absorption coefficient for integrating time 1 s. A practical example of spectral line record (OCS, line intensity $1.3 \cdot 10^{-3}$ cm^{-1} at 413 336.845 MHz) depicted into insertion.

4. Conclusion

The suggested frequency multipliers extend useful range of commercial frequency synthesizers (26-118 GHz) well into submillimeter wave band. Easy for fabrication, inexpensive waveguide mounts have quite high frequency conversion efficiency for resistive type of harmonic generators. Maximum measured output power for tripler was about 3 dBm, and about 1 dBm for doubler. The absence of external tunings, biasing, and resistive principle of harmonic generation greatly simplifies their use and mounting of planar Schottky diodes in such constructions. Grounding of diode leads prevents them from accidental destroying by static electricity what prolongs diode's life.

For practical purposes of molecular spectroscopy as line observing and their analysis the suggested frequency multipliers together with existing millimeter wave synthesizers are quite satisfactory up to 500 GHz.

Acknowledgments

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