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Transmission-Type Harmonic Mixers of MM-wave Range

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Abstract A new kind of harmonic mixer for use in phase locking systems for MM-wave oscillators is presented. The mixer has compact design and combines directional coupler and conventional harmonic mixer in one element. Construction and features of the mixer are discussed. Experimentally measured main characteristics of the mixer are presented. Possibility of continuous frequency scan of phase locked MM-wave oscillator within a full waveguide band is demonstrated.

Keywords Harmonic mixer · MM-waves · Phase locking system

1 Introduction

MM-wave range harmonic mixers are widely used to extend the range of microwave test and measurement equipment, such as spectrum analyzers, frequency counters, power meters and other similar instruments. A broad variety of different mixer constructions covering whole MM-wave range waveguide bands are developed and commercially available [see e.g. 1–3].

These harmonic mixers are also necessary for applications involving accurate frequency sampling such as phase-locked oscillators, frequency linearizers *etc.* In this second case, contrary to the first one, only fraction (and preferably the smallest one) of the oscillator power should be directed to the mixer while the other part is used for the particular application. To the best of our knowledge all existing MM-wave range harmonic mixers are of “dead-end” type in regard to incoming signal radiation. That is in ideal case all incoming radiation is transformed into electrical current through a non-linear element of the mixer and nothing is reflected back. Such construction is very logical for the first kind of mixer applications and is based on demand of maximal mixer efficiency, but for the second kind

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of applications this assumes the use of a directional coupler for a MM-wave range oscillator radiation as inherent part of the mixing circuit. The use of this additional element entails some MM-wave power loss due to extra flange-to-flange waveguide connection and appearance of extra power-frequency dependences. Use of directional coupler also increases weight and size of a whole device that is undesirable especially for satellite-base instruments such as, for example, MM-wave radiometers widely used nowadays for atmosphere remote sensing and for interstellar space researches. In this paper we report about development of series of full waveguide band transmission-type harmonic mixers destined in particular for use in phase-lock loop (PLL) frequency stabilization system for broadband backward-wave oscillators (BWO) produced by Research and Production Corporation “Istok” [4]. The mixers principal layout is discussed and examples of main working characteristics are presented.

2 The mixer layout

Our goal was to develop compact construction of harmonic mixer that could be fixed at BWO output flange so the major fraction of the oscillator power passes through the short mixer’s fundamental mode rectangular waveguide section for further use and its smaller fraction (historically called radio frequency (RF) signal) is split inside the section and used for producing a beat-note signal at intermediate frequency (IF) with harmonics of our 8–14 GHz microwave (MW) synthesizer (that plays a role of a local oscillator (LO) in our scheme) and further frequency stabilization of the BWO by PLL. The mixer should not have any tuners and allow stable operation of the PLL in a full frequency band of MM-wave range BWOs (36–53, 53–78, 78–118 and 118–178 GHz) having 3–30 mW of output radiation power. It was decided to employ a pair of planar Schottky diodes as a non-liner element of the mixer. Anode-to-cathode connected diodes form together antisymmetric current-voltage characteristics that makes the mixer more protected against static and electromagnetically induced electricity while its connection to other elements. This protection requirement limited our choices by balance mixer schemes. A microstrip transmission line structure combining a LO feed-in part and IF outlet including built-in diplexer separating IF from LO had to be developed for the mixer.

Four harmonic mixers were constructed corresponding to four aforementioned frequency bands and in accordance with demands listed above. All mixers have practically identical design differing by size of waveguide only (2.6×5.2, 1.8×3.6, 1.2×2.4 and 0.8×1.6 mm corresponding to BWO output waveguides). Photograph of mixers is presented in Fig. 1. Sketch of the mixer is shown in Fig. 2. The mixer consists from two gold-plated brass blocks. The upper block is just a cover but the lower block contains all main elements of the mixer including diodes, LO and IF connectors and a microstrip transmission line structure that forms coupling, filtering and conducting elements. The rectangular microstrip transmission line structure (conducting strips of the structure are shown in Fig. 2 by dark gray) is fixed inside special dip at the block. Corresponding dip is also made in the upper block just above the structure. Two outer strips of the structure are grounded to the body of the mixer. Standard chassis mount coaxial SMA connectors corresponding to LO and IF ports of the mixer are connected to two inner strips of the structure as shown in Fig. 2. Connection to the IF port is made through small additional inductance coil (not shown) to cut off LO signal and its harmonics from IF circuits. Planar diodes (shown by black color in the insertion in Fig. 2) are glued to the structure by current conductive glue near the edge of the structure. The fundamental rectangular waveguide passes through both blocks of the

Fig. 1 Photograph of mixers.

mixer. In the lower block the edge of the waveguide coincides with the edge of the microstrip structure. Thus, when both blocks of the mixer are joined, diodes are found in the narrow slit in the bigger side of the waveguide. BWO power propagating through the waveguide induces AC current at the radiation frequency going along the slit in opposite directions relatively the center of the wide wall of the waveguide. This current induces corresponding AC current in diodes as in parallel conductors. Therefore, with respect to the

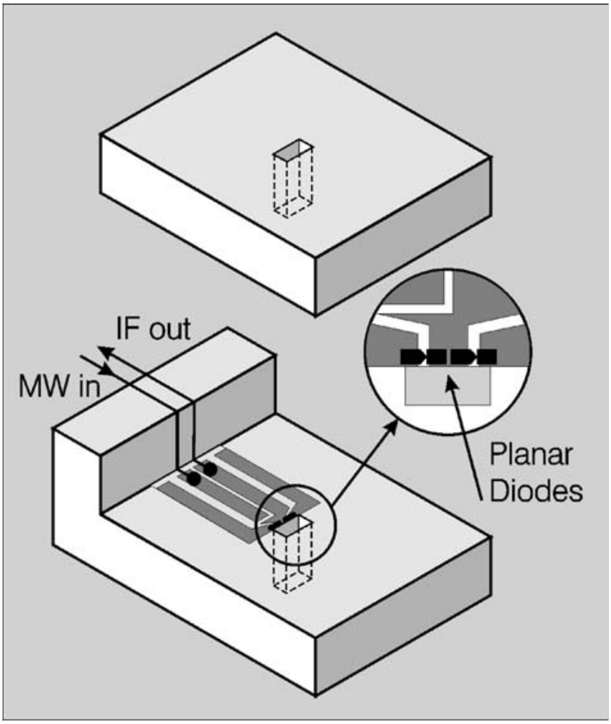


Fig. 2 Sketch of the mixer.

MM-wave (RF) signal the diodes are connected in parallel and in counter direction. The RF voltage is applied to both diodes in the same phase. Fraction of the BWO power transformed into the current through diodes depends on the width of the slit and on the remoteness of diodes from the waveguide edge.

MW synthesizer power goes to diodes through the microstrip transmission line structure. The structure forms 3 dB directional coupler for the MW signal and provides phase difference equal to π between the MW (LO) voltages applied to the diodes.

IF signal is taken from the middle point between anode to cathode connected diodes so the IF current can be expressed as: $I_{IF} = I_{D1} - I_{D2}$, where I_{D1} and I_{D2} are currents through 1-st and 2-nd diode correspondingly. The currents in turn can be written through corresponding applied voltages V_{D1} and V_{D2} and non-linear I-V characteristic of the diode ($I = NL(V)$, the function can be modeled using either exponential or polynomial approximation of real I-V curve). Both voltages V_{D1} and V_{D2} are sum of RF and LO harmonical signals with corresponding frequencies ω_{RF} and ω_{LO}. Accounting for phases of these signals one can get for time dependence of the IF current:

$$\begin{aligned} V_{IF}(t)/R = & NL_{D1}\left[U_{RF}^{D1}Cos(\omega_{RF}t+\varphi)+U_{LO}^{D1}Cos(\omega_{LO}t+\pi)\right] \\ & -NL_{D2}\left[U_{RF}^{D2}Cos(\omega_{RF}t+\varphi)+U_{LO}^{D2}Cos(\omega_{LO}t)\right] \end{aligned}, \tag{1}$$

where U_{RF} and U_{LO} are amplitude of signals; φ is arbitrary phase shift between RF and LO oscillations does not affecting the result but added here just for generality of the expression; R is the IF signal load. Amplitude of IF signal at frequency ($\omega_{RF} - \omega_{LO} \cdot n$), where $n = 1, 2, 3...$, can be obtained by applying Fourier transform function to V_{IF} (t). It should be noted that in an ideal case, when both diodes have identical I-V characteristics and amplitude of RF and LO voltages applied to diodes are equal ($U_{RF}^{D1} = U_{RF}^{D2}$ and $U_{LO}^{D1} = U_{LO}^{D2}$), only odd harmonics of LO will produce IF signal. However, even 10% difference in either LO or RF voltage amplitude entail practically monotone decreasing sequence of IF signals corresponding to consequential harmonics of LO.

Commercial planar Schottky diodes of type of A91147-1 produced by Research-Production Enterprise “Salut” (Nizhniy Novgorod city, Russia) were used. The diode dimensions are 0.1×0.5×0.01 mm. Typical parameters of the diode are following: series resistance R_S = 10 Ohm, total capacitance C_0 = 0.008 pf, dissipated RF (cw) power 15 mW, cut-off frequency f_c=5 THz. Static voltage-current characteristic of the non-linear element of the mixer recorded from the IF output at the absence of BWO and LO power is shown in Fig. 3.

3 Results of testing

All mixers were tested with radiation sources from our resonator spectrometer [5] and demonstrated very similar characteristics. Since the main objective of this paper is not quantitative comparison of different harmonic mixers but demonstration of principal features of the new design we present here only characteristics of the 78–118 GHz range mixer as a typical representative of the series.

In the first test we determined a fraction of the BWO power split by the mixer from the total output. Commercial power meter was used to measure radiation power at the BWO flange in a working frequency range of the BWO. Then the mixer was attached and measurements were repeated at the same radiation frequencies.

Resulting dependences are shown in Fig. 4 by dashed and solid curves correspondingly. Thus the measurements included radiation losses due to additional flange-to-flange connection as well as uncertainty related to somewhat change of the BWO radiation

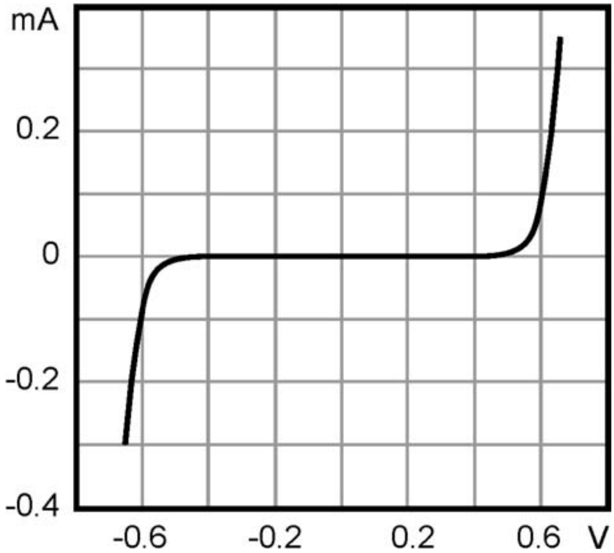


Fig. 3 Static electrical characteristic of the mixer non-linear element.

interference pattern. However, one can see that overall power loss is less than 10%. In this particular experiment for the average relative power loss we obtained 4.2±3.4%.

For the second test we attached our MW synthesizer to the mixer LO input, found a beat note signal between 9-th harmonic of the synthesizer and the BWO oscillating near 90 GHz and determined power of this signal at the IF output of the mixer versus the synthesizer power. The measurements were performed at 350 MHz corresponding to IF in our PLL at the output of IF amplifier and then were recalculated to its input. The result is presented in Fig. 5 by solid curve.

For the next test we inserted a calibrated multiturn attenuator (0–50 dB) between the BWO output flange and the mixer, and measured power of the same beat note signal versus the BWO power. In this test the MW synthesizer output power was fixed at 14 mW. Resulting dependence is shown in Fig. 6 by solid curve.

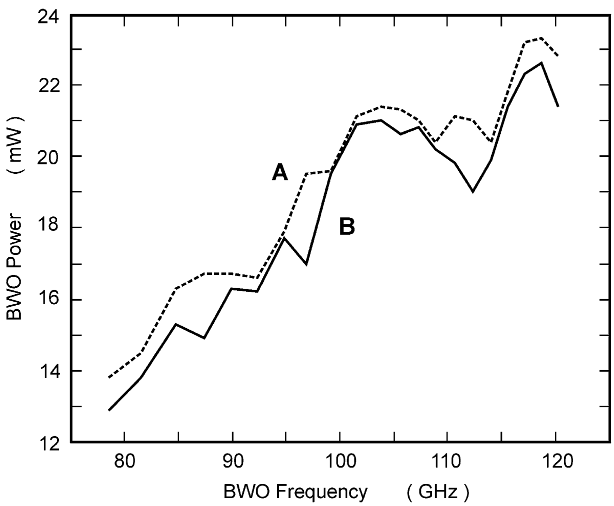
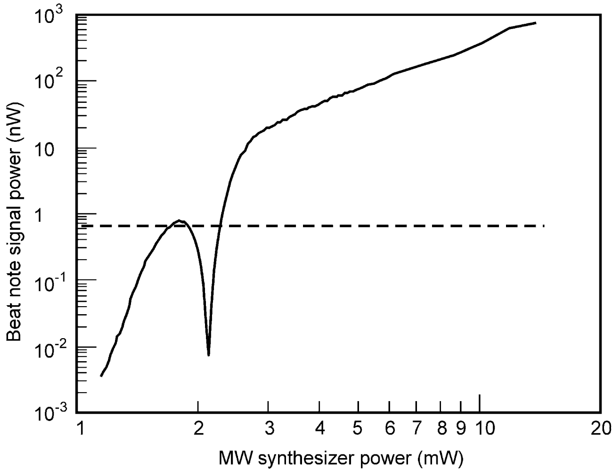


Fig. 4 Output power of the BWO without (dashed line) and with (solid line) the mixer attached to its flange.

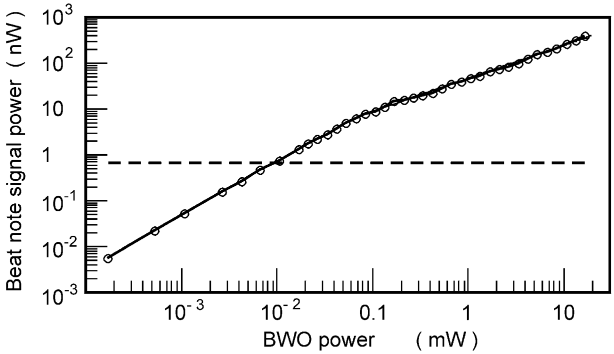
Fig. 5 Power of 350-MHz IF signal produced by the mixer as a beat note between BWO oscillating near 90 GHz and 9-th harmonic of MW synthesizer versus the BWO power. Dashed line corresponds to minimal IF power level necessary for stable operation of our PLL.



Then we locked the BWO oscillations phase stabilization loop and determined the minimal IF power level necessary for stable operation of the PLL. This power level (0.65 nW) is shown in Figs. 5 and 6 by dashed lines. One can see that with the power available we have about one order of magnitude for the MW synthesizer power and about 3 orders of magnitude for the BWO power in reserve to compensate amplitude-frequency dependences of signals during frequency scanning.

In the next experiment we tested feasibility of the BWO continuous frequency scan within its entire working range in a phase-locked regime with use of the mixer. We could just to check if power of the IF signal is always above the minimum level during the BWO frequency scan at some fixed power of the MW synthesizer. However we decided that it would be more informative if scanning the BWO radiation frequency we measure dependence of power of the synthesizer producing the beat note signal with some fixed power exceeding the minimum power level sufficient for the PLL stable operation. For certainty we chose the IF power level of 3.5 nW. So in the experiment after every change of the BWO radiation frequency we adjusted power of the MW synthesizer to keep power of the IF signal constant. Full BWO power was used in this test. At 9-th harmonic of MW synthesizer we were able to scan the BWO radiation frequency from 70 up to 120 GHz that is even slightly wider than a passport range of the oscillator. Results of this test are presented in Fig. 7 by gray circles.

Fig. 6 Power of IF signal produced by the mixer at 350 MHz corresponding to a beat note between BWO oscillating near 90 GHz and 9-th harmonic of MW synthesizer versus the BWO power. Dashed line corresponds to minimal IF level necessary for stable operation of our PLL.



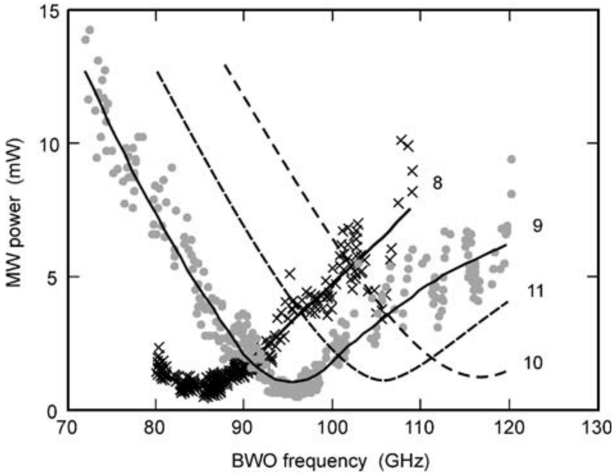


Fig. 7 Power of MW synthesizer required for unchanged (at the level of 3.5 nW) IF signal versus frequency of the BWO phase locked against harmonic of the MW synthesizer. Measured power for 9-th and 8-th harmonics are shown by circles and crosses respectively. Solid curves are result of smoothing of experimental points. Dashed curves correspond to estimated average power for 10-th and 11-th harmonics.

Thus, the test demonstrated that with 12 mW of MW power we could continuously scan whole frequency range of the BWO in phase-locked regime without any adjustments. Then we repeated the experiment scanning the BWO in the range 80–109 GHz at the 8-th harmonic of the synthesizer. We believe that IF signal at this even harmonic number appears due to non-perfect symmetry of diode positions in the construction leading to non-equal values of both RF and LO voltages applied to the first and second diode of the mixer as discussed in previous section of the paper. Measurements at 8-th harmonic are indicated in Fig. 7 by crosses. Spread of experimental points in both experiments appears as a result of summed influence of amplitude-frequency characteristics of all related hardware in the test. Thick solid curves in the figure correspond to smoothing of experimental points. One can see that both dependences are very similar to each other except for about 10-GHz frequency shift related to different harmonic number. The similarity becomes even more obvious if the experimental points are plotted versus the MW synthesizer frequency. In this case dependences have clear resonant character with center near 10.5 GHz and width at half amplitude of about 2–3 GHz. Both dependences practically coincides within the spread of the points, although the 9-th harmonic points are in average a little higher that reflects some decrease of the mixer efficiency with increased number of harmonic. In fact the efficiency drop should be bigger but in this test it was compensated by the BWO power increase with increase of radiation frequency (see Fig. 4). On the base of 8-th and 9-th harmonic curves similarity we could estimate average power of MW synthesizer necessary for the BWO frequency scan at 10-th and 11-th harmonics. These dependences are shown in Fig. 7 by dashed curves.

4 Discussion and conclusions

It should be noted that aforementioned coincidence of dependences of required MW synthesizer power corresponding to 8-th and 9-th harmonics means that major factor determining this particular shape of the dependence is a function of sensitivity of the mixer in respect to LO frequency. This characteristic of the mixer as well as optimal frequency of IF signal is determined by geometry of the microstrip transmission line structure. In particular, length of the strips in our construction was calculated to get optimal LO frequency corresponding to central frequency of our MW synthesizer. Of course, LO and IF frequency ranges can be adapted to any particular demand. On the contrary, the frequency range of controlled signal is fixed by the size of fundamental mode waveguide. This is common restriction for fundamental waveguide based constructions, however it limits the use of such kind of mixers with SubMM-wave range BWOs, where oversized multimode waveguides are used and quasioptical solutions (see e.g. [6]) are preferable.

Conversion loss of a harmonic mixer are usually determined as a ratio of the mixer input signal power to the output power of IF signal assuming that optimal power of LO signal is applied. The conversion loss of our mixer can be estimated using Fig. 6 and taking into account aforementioned 4.2% average fraction of power split by the mixer (Fig. 4). Obtained conversion losses versus the BWO power are within 27–33 dB, having minimum at total BWO power near 0.1 mW. For comparison specified conversion losses of "dead-end" harmonic mixers of 75–110 GHz range are 32 dB (QMH-W, QuinStar Technologies Inc. [1]), 35 dB (MHP-10, Millitech Inc. [2]), 46 dB (11970W, Agilent Technologies Inc. [3]).

Thus, results of testing of developed mixers demonstrated their applicability for use in MM-wave range radiation sources PLL systems that allow continuous frequency scanning of the source in a full fundamental waveguide range. Compactness of the construction is evidenced by Fig. 8 where photograph of the 78–118 GHz BWO with attached harmonic mixer is presented. However, we believe that the main result of the paper is demonstration of possibility of a broad-band splitting of small fraction of MM-wave radiation and its efficient use for producing the beat notes with MW signal in a compact transmission-type waveguide construction.

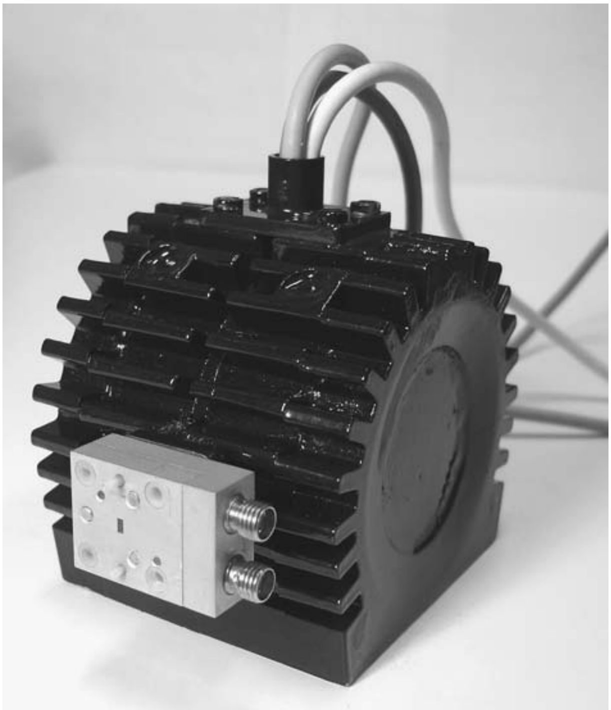


Fig. 8 Backward-wave oscillator of kind of OB-71 (78–118 GHz) with attached transmission-type harmonic mixer.

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