HIGH-STABILITY 72 GHz GUNN OSCILLATOR FOR THE CHARACTERIZATION OF ULTRA-HIGH-SPEED OPTICAL RECEIVERS BASED ON InP AND InSb SCHOTTKY DIODES

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ABSTRACT
A high-stability and excellent spectral purity 72 GHz Gunn oscillator has been realized in order to characterize ultra-wide band Schottky diodes based on intrinsic InP and InSb semiconductors. The developed 72 GHz oscillator shows a relative frequency stability of 2×10^{-9} for observation times of 10 s and a collapse frequency of 4 THz. Preliminary frequency measurements of different lines of a FIR laser demonstrate a good detection efficiency with a typical bandwidth of 1 THz.

Keywords: microwave oscillator, microwave frequency standards, FIR frequency measurements, Schottky diode receivers.

1. INTRODUCTION
Ultra-high speed heterodyne receivers operating in the electromagnetic spectrum range from the visible to the infrared regions find natural applications in the fields of frequency metrology and high-resolution spectroscopy where it is usual to measure wide frequency differences (up to several terahertz) between optical standards. Novel Schottky diodes, based on an electrochemically edged tungsten whisker and intrinsic InP and InSb semiconductor crystals [1], can be used as fast receivers up to a frequency bandwidth of 1 THz. The actual wide frequency measurement methods [2-5] can therefore be simplified or their results can be extent to the near and far infrared regions by means of these novel devices. An efficient frequency down-conversion at optical wavelengths, directly obtained in the Schottky diodes, has to be realized to measure frequencies up to 1 THz. To this purpose the Schottky structure is irradiated with a microwave radiation (up to 100 GHz). This microwave oscillator must therefore have an excellent spectral purity (high degree of temporal coherence) in order to reach the frequency of 1 THz with as low phase-noise as possible, which is a necessary condition to obtain good signal to noise ratio at the receiver output.

2. 72 GHz GUNN OSCILLATOR
A high-stability microwave oscillator at the frequency of 72 GHz was realized to operate as a standard reference in the millimetric region. This frequency reference is based on a Gunn diode frequency stabilized with respect to a low phase-noise Surface Acoustic Wave oscillator at a frequency of 1 GHz. The implemented stabilization set-up is reported in Fig. 1. As a first step, a wide comb of frequencies up to 22 GHz was generated from the 1 GHz reference signal by using a power amplifier (with an output power of 1 W) and a step recovery diode. By

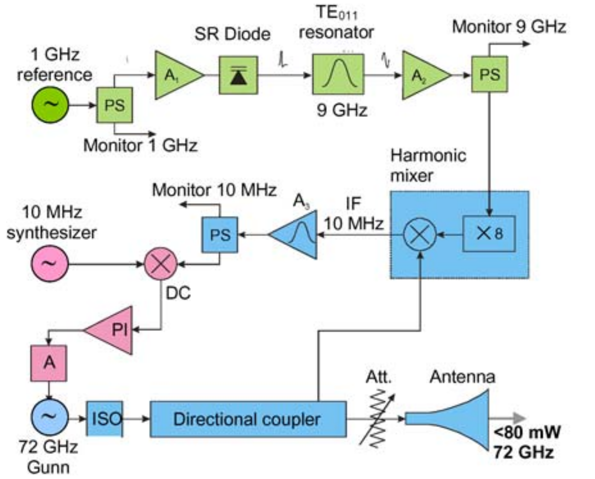

Figure 1. Frequency stabilization set-up for the 72 GHz oscillator. PS power splitter, A frequency actuator, PI proportional and integral servo.

using a cylindrical microwave cavity working on the TE_{011} mode at the resonance frequency of 9 GHz with a quality factor of 6500 (1.4 MHz linewidth) the 9 GHz component was selected from the comb frequencies. The low phase-noise 1 GHz to 9 GHz realized frequency chain prototype is shown in the Fig. 2.

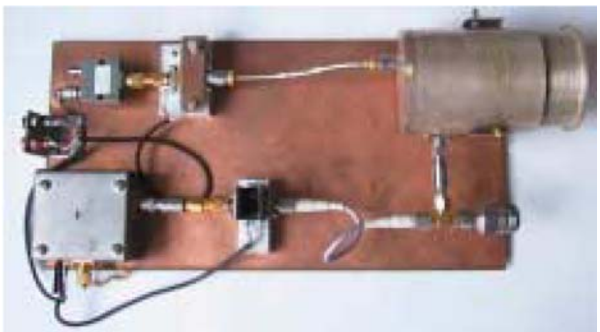

Figure 2. Photograph of the implemented 1 GHz to 9 GHz low phase-noise frequency chain.

A harmonic mixer combines the amplified low phase-noise 9 GHz signal with a small fraction of the 72 GHz radiation. An intermediate frequency (IF) of 10 MHz is generated at the harmonic mixer output. With a selective IF amplifier and a second mixing stage driven by a 10 MHz reference signal (synthesizer), the obtained DC signal, proportional to the phase difference between the 10 MHz signals, was fed to an integrating servo which controls the current, and hence the frequency, of the 72 GHz Gunn diode. When the

72 GHz is locked to the 1 GHz reference with a control bandwidth of ~10 kHz, the medium-term frequency stability of the microwave radiation reaches the relative value of $2x10^{-9}$ for integration times of 10 s (as it is shown in Fig. 3). This stability is two orders of magnitude better than the free-running stability and it is good enough for the proposed frequency measurements and for the characterization the Schottky receivers.

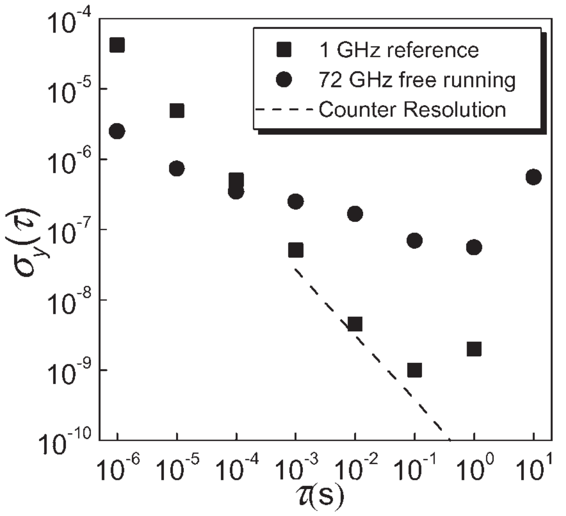

Figure 3. Frequency stability of the 72 GHz oscillator. ● Free-running Gunn oscillator. ■ Gunn oscillator locked to the 1 GHz reference. The dashed line is the counter resolution.

The influence of the servo loop control was also measured by means of the power spectral density of the frequency stabilized 72 GHz oscillator. The diagram reported in Fig. 4 shows the measurement result obtained with an electrical spectrum analyzer. In the locking condition the phase-noise of the 72 GHz is strongly reduced and a narrow emission linewidth is achieved.

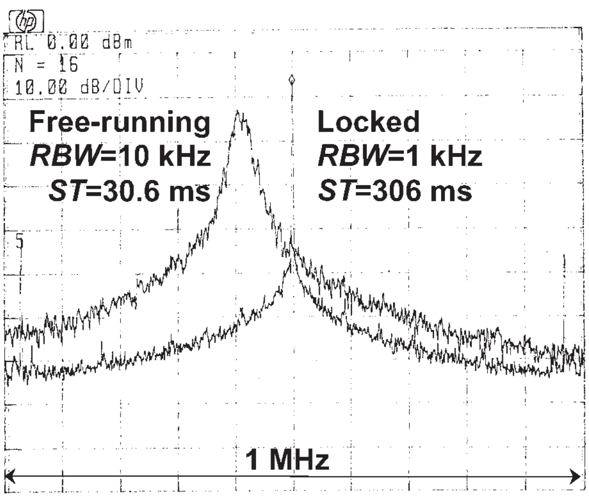

Figure 4. Power spectral density of the 72 GHz Gunn oscillator both in free-running and in locked condition.

From this measurement is possible to extrapolate the residual phase noise of the microwave oscillator. The estimated phase noise can be approximated with a white contribution at a level of–75 dBc/Hz for Fourier frequencies in the range from 1 Hz to 10 kHz. In this way the collapse frequency is [6]

$$\nu^{col} = n^{col}\nu_0 = \frac{\nu_0}{\sqrt{\phi^p(\nu_0)}} \qquad (1)$$

where ν_0 is the central frequency of 72 GHz, ν^{col} is an integer number which defines the maximum frequency multiplication order, and $\phi^p(\nu_0)$ is the total phase noise power defined as

$$\phi^p(\nu_0) = \int_{f_0}^{\infty} S_\phi(\nu, f)\,df \cong 1 \qquad (2)$$

In this case a collapse frequency of ~4 THz is obtained from the integral (2). The obtained high degree of temporal coherence (narrow linewidth) enables to observe in the Schottky diode high order mixing products with excellent signal to noise ratio being the microwave power strongly concentrated around the carrier.

3. NOVEL SCHOTTKY DIODES

The investigated diodes present two types of contact. InP-diodes have a honeycomb structure with window diameters of 1.65 mm and 1.5 mm; they were produced in the Semiconductor Institute (Tomsk, Russia), in collaboration with the Institute of Laser Physics (Novosibirsk, Russia). The InSb-diode has a classic point-contact structure with a large semiconductor platelet as the post and was assembled in the Physics Department of the Pisa University. The contacts to the semiconductor posts are made by a tungsten whisker, electrochemically etched to the desired tip radius by means of a 2N solution of NaOH. The wires are 30 mm in diameter, and the radii of curvature of the tips were of 50-60 nm. A Scanning Electron Microscope was used in order to control the curvature radii and the geometry of the contacts. In the case of InP a thin, 20~nm, gold layer was sputtered on the surface of the crystal to ensure the mechanical stability of the contact.

The optical responsivity of these structures was characterized at the wavelengths of 0.45 μm, 0.48 μm, 0.514 μm, 0.633 μm, 0.98 μm, 1.064 μm, 1.54 μm, 2.097 μm, 10 μm, 100 μm and 560 μm using respectively argon, helium-neon, semiconductor, Nd:YAG, Er-Yb:glass, Tm-Ho:YAG, CO_2 and CH_3OH lasers. For the first time these devices were characterized in the near infrared region at the Nd:YAG, Er-Yb:glass, Tm-Ho:YAG laser emissions. The obtained typical responsivity values are around 10 mV/mW.

4. BEAT NOTE MEASUREMENTS

As a first step in the characterization of the Schottky diodes direct beat note measurements were realized between visible and near infrared lasers. In order to characterize the Schottky diodes as heterodyne receivers it is necessary to employ laser sources with good frequency stability. This condition can be obtained measuring the frequency difference between either two modes of a multi-mode laser or two highly stable lasers.

When two monolithic Nd:YAG lasers at 1.064 μm, with high intrinsic frequency stability, were used, direct beat signals up to a few gigahertz with typical signal to noise ratios of 55 dB were obtained from the characterized Schottky diodes in a measurement bandwidth of 10 kHz and for incident optical powers in the order of tens of milliwatt, as it is shown in Fig. 5.

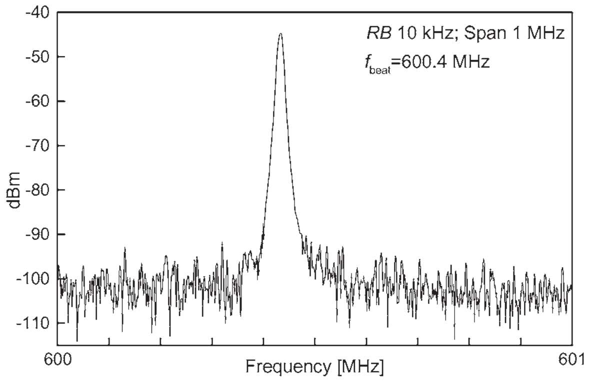

Figure 5. Beat note signal between two single frequency NPRO Nd:YAG lasers.

Similar results were obtained when visible laser sources, like He-Ne and Ar lasers, were employed.

The characterization of the Schottky diodes was afterwards concentrated on the mixing efficiency between the microwave radiation and the optical radiation. We tested the mixing properties of the Schottky diodes in the sub-mm region, by observing the beat note between the FIR radiation emitted from a molecular laser and the Gunn diode harmonics. The FIR laser cavity is an open structure nearly confocal Fabry-Pérot resonator 1 m long. It is pumped through a waveguide CO_2 laser working in long pulse regime. The pumping radiation is coupled into the resonator through a 1 mm hole drilled in one gold coated copper mirror (115 cm radius of curvature). The FIR power is extracted from the cavity by a variable coupler, consisting of an elliptical copper mirror. At each wavelength the output coupling was adjusted by moving the mirror in direction perpendicular to the cavity axes. The FIR radiation was focused onto the junction of the diode by a parabolic copper mirror with a focal length of 1.5 cm. The Gunn radiation at 72 GHz was coupled through a horn to the mixer antenna, i.e. to the whisker. We obtained the optimal coupling when the Gunn waveguide output was very close to the whisker (about 1 mm). The radiation produces on the diode output a rectified video signal and a mixing signal. The video signal due to the Gunn was of the order of 500 mV whereas that one due to the FIR laser was a few millivolt. These signals were used to optimize the system alignment. The mixing efficiency of the diodes was tested at the moment up to the tenth harmonic of the Gunn frequency. We have not observed appreciable change in the signal to noise ratio of the beat note with the mixing order. In all the cases the signal to noise ratio was of the order of 25 dB in an observation bandwidth of 10 kHz. A similar sensitivity was obtained for both InP and InSb substrates. The diodes did not need any dc bias, because the Gunn diode power was sufficient to polarize the junction. As an example, the diagram reported in Fig. 6 shows the obtained beat note signal between the tenth harmonic of the Gunn oscillator and the HCOOH (formic acid) FIR laser emission.

The molecular laser lines that we tested were chosen in the spectrum of different isotopomers of formic acid. We measured lines at 296999.2 ± 0.5 MHz (by fourth harmonic mixing) from DCOOD pumped by the 10R(20) CO_2 component, at 429837.7 ± 0.4 MHz (sixth harmonic) from DCOOH pumped by the 10R(36), at 716155.7 ± 0.8 MHz (tenth harmonic) from HCOOH pumped by the 9R(22).

The results of these measurements, summarized in the

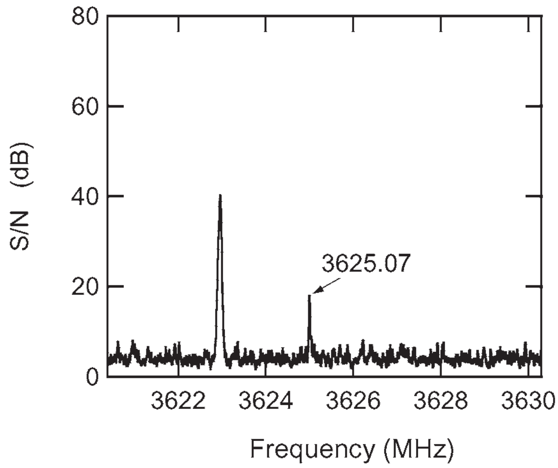

Figure 6. Beat note signal between the 10th harmonic of the 72 GHz and the HCOOH FIR laser.

Table 1, are always in good agreement with the previous measurements reported in the literature.

FIR Frequency	Gunn harmonic	CO_2 component
296 999.2 ± 0.5 MHz	4ª	10R(20)
429 837.7 ± 0.4 MHz	6ª	10R(36)
716 155.7 ± 0.8 MHz	10ª	9R(22)

Table 1. Frequency measurements of the emission lines of the different isotopomers of formic acid FIR laser.

5. CONCLUSION

A high-stability and excellent spectral purity 72 GHz Gunn oscillator was realized in order to characterize ultra-wide band Schottky diodes. The developed 72 GHz oscillator shows a relative frequency stability of 2×10^{-9} for observation times of 10 s and a collapse frequency of 4 THz. A new type of Schottky diode has been tested as ultra-high speed heterodyne receivers using the developed microwave standard. Beat-note between the harmonics of a fixed-frequency microwave oscillator at 72 GHz and FIR molecular laser radiation has been detected up to 720 GHz, with a good signal-to-noise ratio. The fact that we do not observe a fall in efficiency increasing the beating order would assure that we might have efficient detection at frequencies higher than 1 THz.

The final experimental target will be the wide frequency difference measurements (up to several terahertz) between optical standards in the visible and near infrared region by means of the realized frequency stabilized 72 GHz oscillator and the novel Schottky receivers.

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