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# Millimeter Wave Generation Using a Uni-Traveling-Carrier Photodiode

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## Abstract

We have designed a new photomixer using a uni-traveling carrier photodiode (UTC-PD) for generation of W-band radiation. The UTC-PD is integrated on a InP chip with DC and RF circuits and the chip is mounted upside down on a fused quartz substrate which is placed in a microstrip channel across a quarter-height W-band waveguide. A simple cross-shaped microstrip-waveguide transition printed on the quartz substrate is used to couple power into the waveguide. From the simulation it is found that this microstrip-waveguide transition can give better than -15 dB return loss over 75–120 GHz. The UTC-PD is irradiated by combined two lasers from the back side of the InP chip. We have successfully produced difference-frequency radiation at 100 GHz with a power level of $\sim$1 mW by the photomixer.

## Introduction

Millimeter- and submillimeter-wave heterodyne mixers based on the Superconductor-Insulator-Superconductor (SIS) junctions have used a local oscillator (LO) source which is a combination of a Gunn diode and multipliers. Since the LO source with the combination of a Gunn diode and multipliers has a mechanical complexity and poor frequency coverage especially at submillimeter wavelength, a compact and mechanically-simple LO source with broad frequency coverage is highly required for submillimeter-wave SIS receivers in the radio telescopes. Photomixers, which generate a difference frequency of two diode lasers at millimeter and submillimeter wavelength by photoconductive mixing, have been alternatively developed.[1, 2] Photomixers are so compact solid-state sources with broad frequency tunability that they meet the requirement for the LO source of the SIS receivers at millimeter and submillimeter wavelengths.

The low-temperature-grown (LTG) GaAs films have been prevailingly used for a photomixer element. Although the LTG-GaAs photomixers can provide enough output power for a few applications such as molecular spectroscopy, improvement of the output power is highly required for many applications. It has been recently shown that photomixers using a uni-traveling photodiode (UTC-PD) have a great potential for generation of millimeter-wave radiation with a bandwidth as high as 220 GHz [3]. Based on a simple analysis, it is expected that a 3-dB falloff bandwidth of the UTC-PD determined by carrier traveling time can be in a THz range [4]. The UTC-PD photomixer has emerged as one of the promising candidates to generate the millimeter- and submillimeter-wave radiation.

We have designed a new photomixer using the UTC-PD for generation of W-band radiation. In this paper, a detailed design of the photomixer at W band using the UTC-PD and preliminary results of millimeter-wave generation experiments at 100 GHz will be presented.

## Instrument Design

### *A. UTC-PD device*

Since an upper frequency of photo-response in a photodiode is usually limited by a carrier traveling time in a depletion layer in the photodiode, reduction in thickness of the depletion layer is necessary for increasing the upper frequency of photo-response. However, the reduction in thickness of the depletion layer is inevitably accompanied with an increase of capacitance of the photodiode. As a result, the upper frequency of photo-response is sometimes limited by a time constant of the photodiode.

In the UTC-PD, a relatively thick depletion layer made of a wide band-gap material such as InP is adopted to avoid the increase of the diode capacitance. A schematic energy diagram of the UTC-PD is shown in Fig. 1. Photocarriers are generated in an absorption layer of p-type InGaAs and drift into the depletion layer (or collection layer) made of InP. The electron velocity in the InP layer is so high that the traveling time in the depletion layer can be small. Therefore, very fast photo-response in the UTC-PD can be expected.

A 6-$\mu$m UTC-PD is integrated on a 150-$\mu$m-thick semi-insulating InP chip with DC and RF circuits. A photograph of the UTC-PD chip is shown in Fig. 2. The UTC-PD is assumed to have 25-$\Omega$ resistance in parallel with capacitance of 20–30 fF during design of the RF circuit. The UTC-PD is coupled with a tapered stripline transition which transforms an output impedance of the UTC-PD to 50 $\Omega$. The diode capacitance is tuned out by a parallel inductance terminated by radial stubs as RF shorts.

### *B. Photomixer mount*

We have designed a photomixer using the UTC-PD for generation of W-band radiation. Because of efficient transmission of power over a broad bandwidth, our photomixer mount uses waveguide at its output. The UTC-PD chip is placed in a shielded microstrip channel in order to simplify integration of impedance transformers and filters into the photomixer mount.

A simple cross-shaped probe of microstrip-to-waveguide transition printed on a quartz substrate is used to couple power into the waveguide. A surface of the quartz substrate, on which a conducting microstrip is printed, is oriented to an waveguide backshort.[5] Since it is well known that reducing height of an waveguide is effective to extend a operation bandwidth of the transition, a quarter-height waveguide is employed in the mount. A photograph of the waveguide probe is shown in Fig. 3.

The diode chip is soldered upside down on a 0.58-mm wide and 0.15-mm thick fused-quartz substrate as shown in Fig. 3. RF output of the diode is coupled to a stripline with a characteristic impedance of $\sim$80 $\Omega$ through 2-stage stripline impedance transformers and then transferred to the quarter-height waveguide by the transition probe. The end of the microstrip channel is short-circuited at some length from the waveguide in order to make a return path of the DC bias applied to the diode. Choke filters made of high- and low-impedance striplines on the quartz substrate are placed in the other end of the microstrip channel. DC bias is applied to the diode through the choke filters. The diode is irradiated by combined two lasers from the back side of the UTC-PD chip. A cross section of the photomixer mount is schematically shown in Fig. 4.

Simulations of the waveguide-stripline transition including the stripline and the impedance transformers were performed using HP's High Frequency Structure Simulator (HFSS) to determine the optimum lengths of the waveguide backshort and the microstrip channel. Figure 5 shows the best bandwidth performance of the transition predicted by the simulation. It is clear that this microstrip-waveguide transition can give better than -15 dB return loss over 75–120 GHz.

## Result and discussion

Lasers ($\lambda = 1.5\mu$m) provided by two semiconductor laser-diodes are separately transferred to optical fibers and then coupled by a coupler into an optical fiber. The output of the lasers from the optical fiber are focused onto the UTC-PD by a lens located in the photomixer mount. The position of the lens is precisely aligned against the photodiode so that maximum power of millimeter-wave radiation is available at the output port of the photomixer mount. The output millimeter-wave radiation from the photomixer is detected by a spectrum analyzer with a harmonic mixer (HP11970) or a Schottky-diode detector.

Typical DC I-V curves of UTC-PD's used in experiments are shown in Fig. 6. The bias voltage applied to the diode is usually in the range from -1 to -2 V. It has been shown that photocurrent of the UTC-PD induced by lasers is approximately proportional to the amount of laser power coupled to the diode in the experiment at lower frequency.[6] In the similar manner, we first measured output radiation power near 100 GHz as a function of photocurrent of the UTC-PD. In Fig. 7 output power measured by a Schottky-diode detector is plotted as a function of the photocurrent of the UTC-PD for bias voltages of -1, -1.5, and -2 V. It is clear that the output power increases in proportion to the photocurrent (or the input laser power) at lower photocurrent. However, a compression or saturation of output power is observed at higher input laser power. The compression or saturation of output power is usually explained by the space charge effect.[7] The output power weakly depends on the bias voltage and increases a little as the bias voltage increases. At the bias voltage of -2 V and photocurrent of 20 mA, highest output power of a half mW is observed.

In Fig. 8 a spectrum near 100 GHz of photomixer output measured by the harmonic mixer is shown. The peak power in Fig. 8 is about 0.7 $\mu$W, which is calibrated from the conversion loss of the harmonic mixer given in an attached data sheet. Width of the output spectrum of the photomixer is less than 10 MHz, which is mainly governed by fluctuation of frequencies of the two lasers, since freely-running lasers are used in the experiment.

## Summary

We have exploited a photomixer for generation of millimeter wave at W band using a UTC-PD. We have successfully observed output of millimeter-wave radiation at 100 GHz and obtained output power as high as approximately 1 mW. As far as we know, this is the highest output power ever generated by any kind of photomixers at this frequency band. The bandwidth of the output of the UTC-PD photomixer is less than 10 MHz, which is probably limited by the fluctuation of input lasers.

## Acknowledgment

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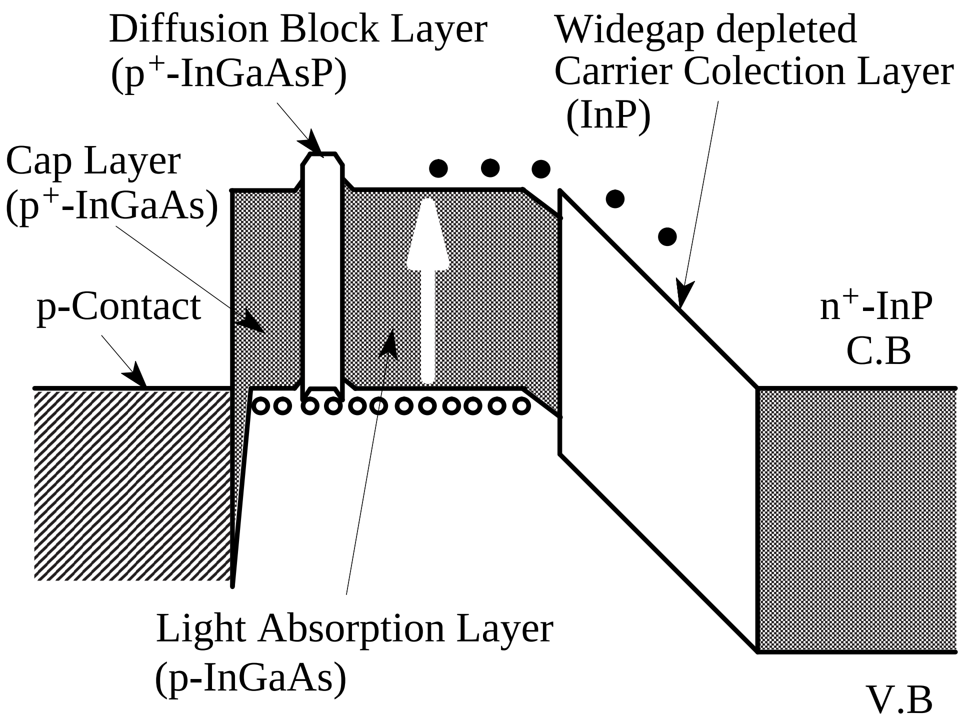


Fig. 1 Schematic energy band diagram of a UTC-PD.

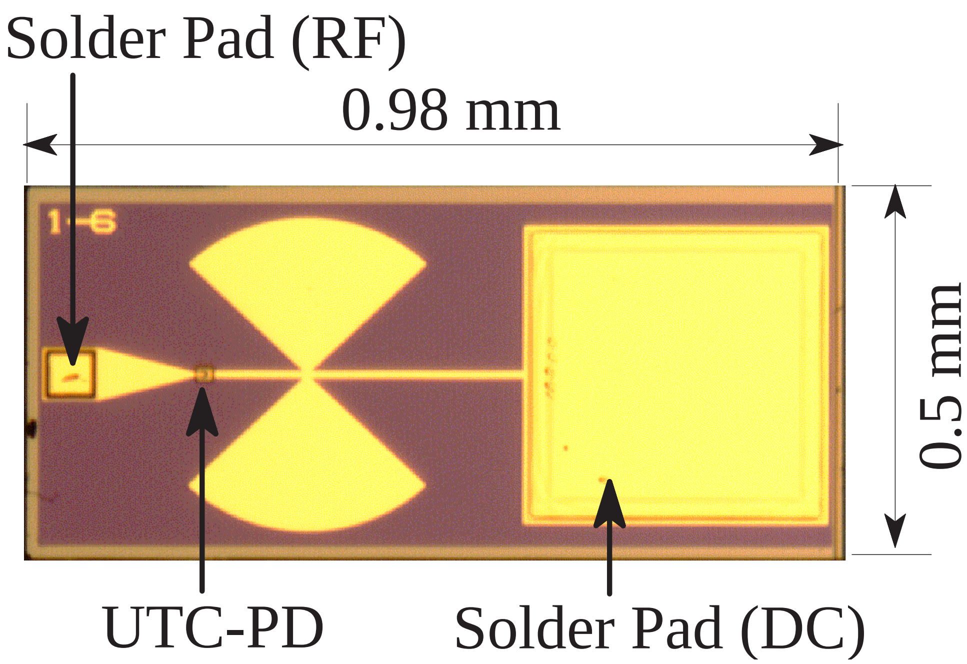


Fig. 2 Photograph of a UTC-PD chip.

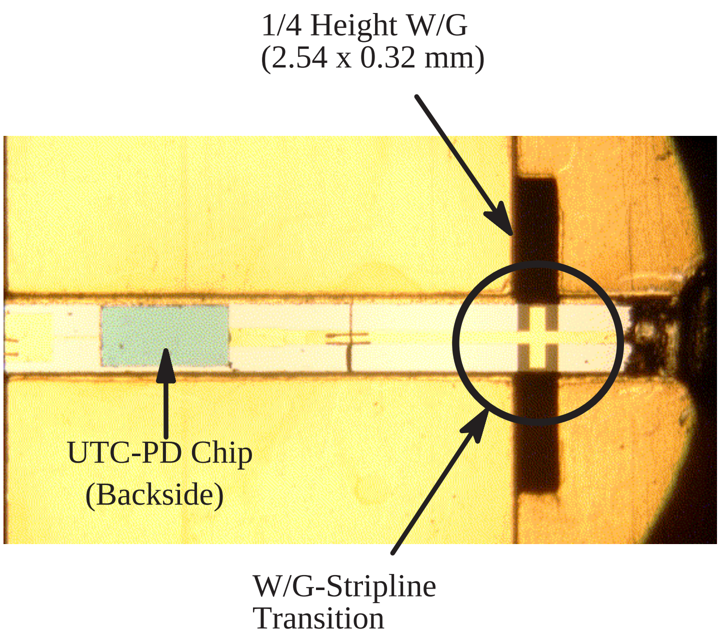


Fig. 3 Waveguide-stripline transition and UTC-PD mounted on a quartz substrate.

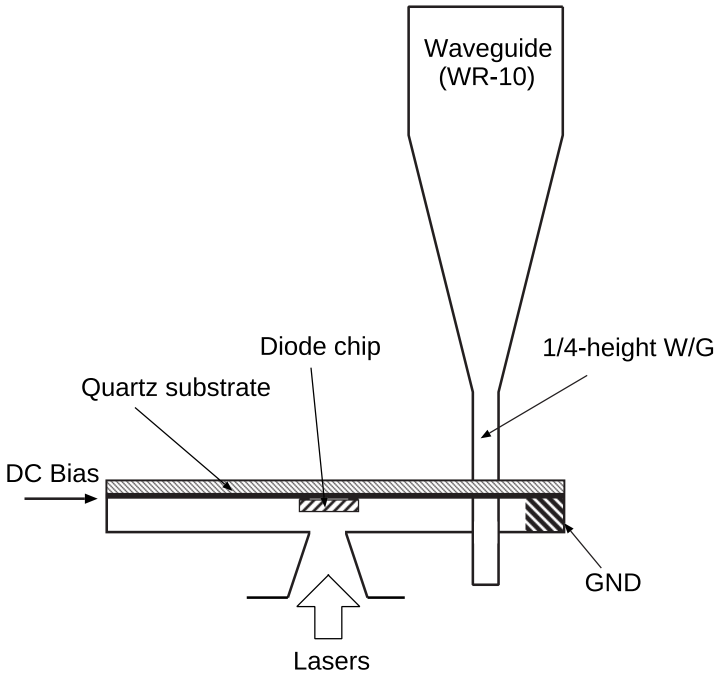


Fig. 4 Schematic of a photomixer mount.

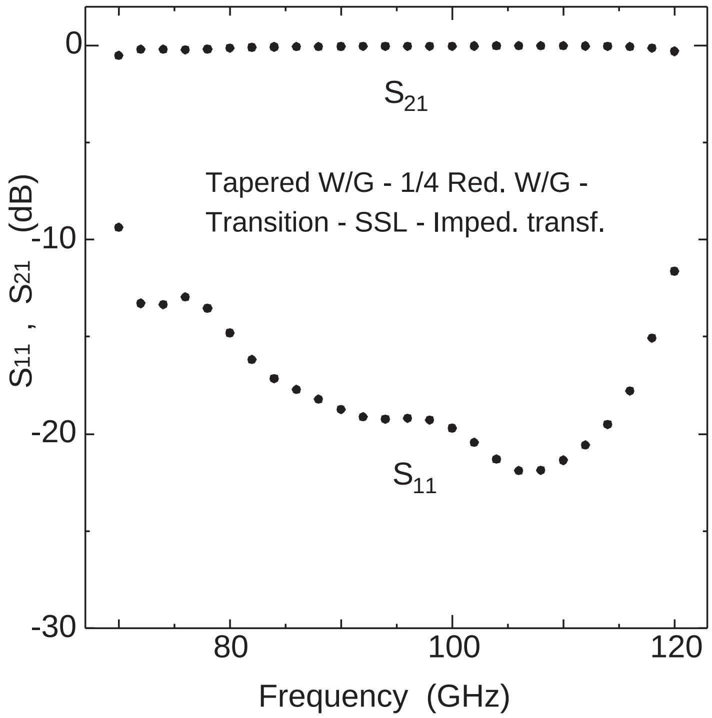


Fig. 5 Predicted performance of the waveguide-stripline transition.

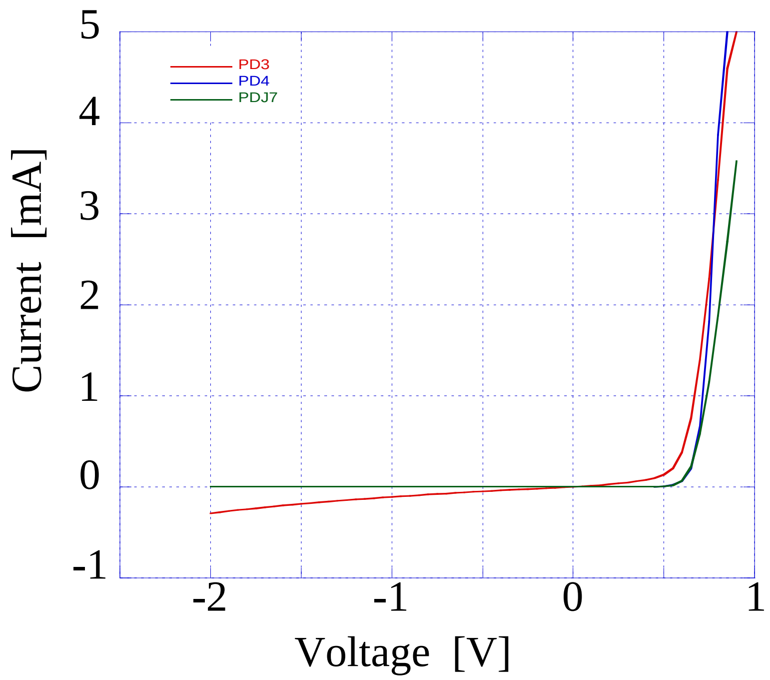


Fig. 6 DC I-V curves of UTC-PD's .

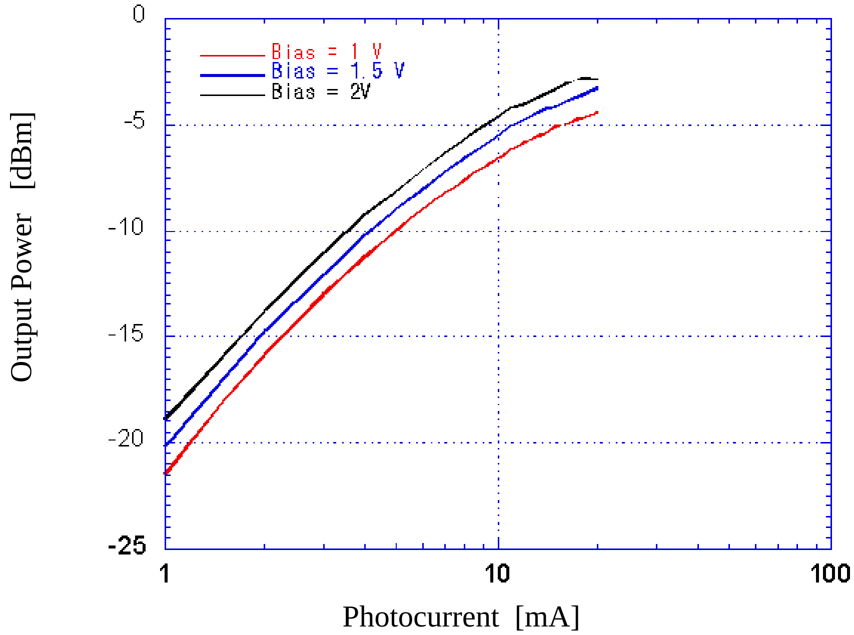


Fig. 7 Millimeter-wave output power as a function of diode photocurrent.

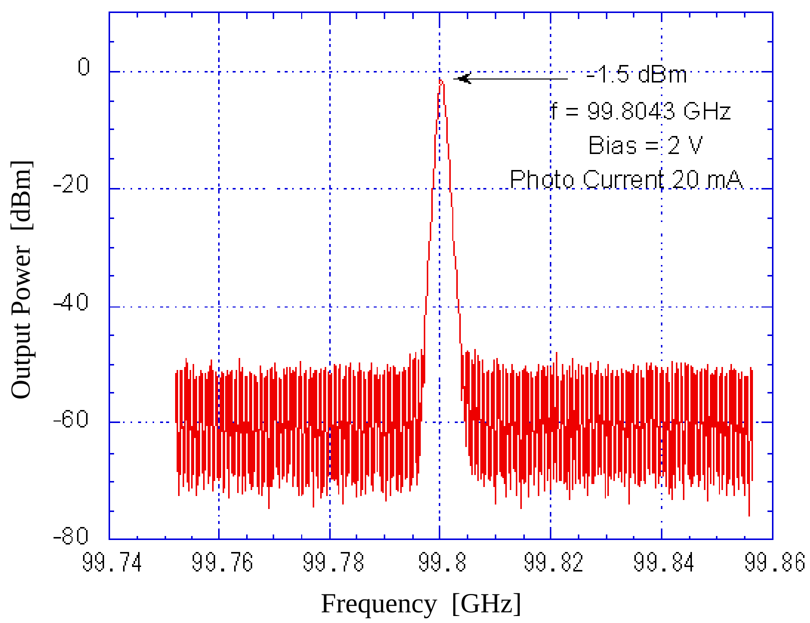


Fig. 8 Spectrum of photomixer output at ~100 GHz.