# F-Band (90-140 GHz) Uni-Traveling-Carrier Photodiode Module for a Photonic Local Oscillator

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## Abstract

A compact uni-traveling-carrier photodiode (UTC-PD) module with a WR-8 rectangular waveguide output port for operation in the F-band (90 - 140 GHz) has been developed. A resonating matching circuit integrated with a UTC-PD and a microstrip-line-to-rectangular-waveguide transformer are designed to realize high output powers with a wide bandwidth covering the F-band. The module size and configuration are equivalent to those of conventional optoelectronic devices, which enables the use of standard assembly technology. The fabricated module exhibits a record millimeter-wave output-power of 17 mW at 120 GHz for a bias voltage of -3 V. The 3-dB down bandwidth is as wide as 55 GHz, which fully covers the F-band. An optical input stress test at a photocurrent of 10 mA performed to confirm the long-term stability of the module showed that the dark current stays below 1 μA for more than 3000 hours.

## Introduction

Photonic generation of millimeter (mm) and sub-mm wave signals is a promising technique for a local oscillator system in radio telescopes [1] because it provides an extremely wide bandwidth and can use low-loss fibers for transmission of very-high-frequency signals. For example, in one of the options proposed for the Atacama Large Millimeter/sub-millimeter Array (ALMA) [2], signals in a very wide frequency range from about 80 to 160 GHz have to be distributed to 64 antennas within an area of ~10 km$^2$. In addition, the use of a high-output-power O/E conversion device can eliminate the costly post amplification circuit and thus simplify the system configuration. Thus, the photonic local oscillator system requires a photodiode that has a high-output-power as well as superior high-frequency characteristics. The uni-traveling-carrier photodiode (UTC-PD) [3] is one of the best solutions, because it provides a high 3-dB down bandwidth ($f_{3dB}$) and a high-saturation-output power simultaneously. To date, excellent performance, an $f_{3dB}$ of 310 GHz [4] and an output power of over 20 mW at 100 GHz [5], has been demonstrated. These features come from the unique operation mode of the UTC-PD in which only electrons are the active carriers traveling through the junction depletion region [3]. For practical use, especially in the frequency range above 100 GHz, the device should be in a module with a rectangular waveguide (WG) output port, because the useful frequency range of the coaxial connector is limited to below ~100 GHz. Although photodiode modules with a waveguide output port have been reported [6, 7], they are generally bulky and incompatible with standard optoelectronic (O/E) device assembly technology. Recently, we have developed a compact waveguide output UTC-PD module for operation in the W-band (75 - 110 GHz) [8]. This module exhibits a very high mm-wave output power of 11 mW at 100 GHz, which is about two orders of magnitude larger than that obtained by a pin-PD module at the same frequency [6]. Despite these promising results, it is still necessary to develop photodiode modules operating at higher frequencies to fulfill the requirements for a much simpler local oscillator system [2].

In the present work, we have developed a WR-8 waveguide output UTC-PD module for operation in the F-band (90 - 140 GHz), which is suitable for use in a photonic local oscillator system. Its size and configuration are equivalent to those of conventional semiconductor optoelectronic (O/E) devices, so that it is compatible with standard assembly/testing equipment for O/E device modules. The module was designed to generate high output power in the F-band, and the output power characteristics as well as the stability for long-term operation were evaluated.

## Design and Fabrication

### *A. Photodiode*

At frequencies above 100 GHz, it is important to implement methods for improving output power because the influence of the CR time constant of the PD becomes significant in a conventional wide-band design. A resonating matching circuit is a promising technique to improve the O/E conversion efficiency, which it achieves by compensating the imaginary part of the internal impedance in the UTC-PD at a designed frequency. The matching allows us to use a relatively large area (large junction capacitance) device to increase saturation photocurrent level and reduce self-heating of the PD. This matching circuit simultaneously acts as an integrated bias circuit, which eliminates hybrid integration of a fine-structure bias-line in the waveguide-output module. Thus, we fabricated a UTC-PD integrated with a short-stub matching circuit [5, 9] (Fig. 1). The stub length was optimized to be 70 μm to make the output power peak at around 120 GHz.

The UTC-PD epi-layers were grown by MOCVD. The absorption layer consists of p-InGaAs (p = $4 \times 10^{17}$ /cm$^3$, 122 nm), p-InGaAs (p = $1 \times 10^{18}$ /cm$^3$, 10 nm) and undoped InGaAs (8 nm), and the collection layer consists of undoped InGaAsP (16 nm), undoped InP (6 nm), n-InP (n = $1 \times 10^{18}$ /cm$^3$, 7 nm) and n-InP (n = $2 \times 10^{16}$ /cm$^3$, 201 nm). The rest of the structure is similar to ones reported previously [3,10]. Hexagonally shaped double-mesa edge-illuminated refracting-facet UTC-PDs with an absorption area (S) of 74 μm$^2$ were fabricated by wet chemical etching and metal-lift-off processes. This relatively large absorption area for increasing the maximum output power is possible because the matching circuit effectively compensates the imaginary part of the internal impedance of the UTC-PD. Each device was integrated with 50-Ω CPWs (one for the output, one for the short-stub) on the InP substrate. These passive elements were monolithically integrated without employing an additional process step in the standard UTC-PD process. The MIM capacitor has a capacitance of 2 pF. Then, the refracting facet structure [11] was fabricated on the side of the PD by using the spontaneous etch-stop nature of InP on the (111)A facet. The side of the device was then anti-reflection coated and the wafer was cleaved into chips. The chip size is 300 μm × 450 μm, and all elements are integrated within this small area. The responsivity measured in a broad-area device at $\lambda$ = 1.55 μm was 0.4 A/W.

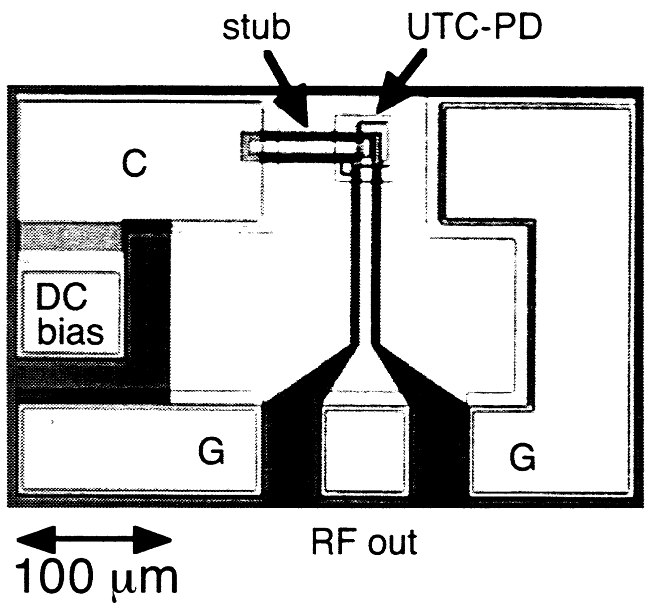


Fig. 1. Micrographs of the fabricated UTC-PD chip with an integrated matching circuit.

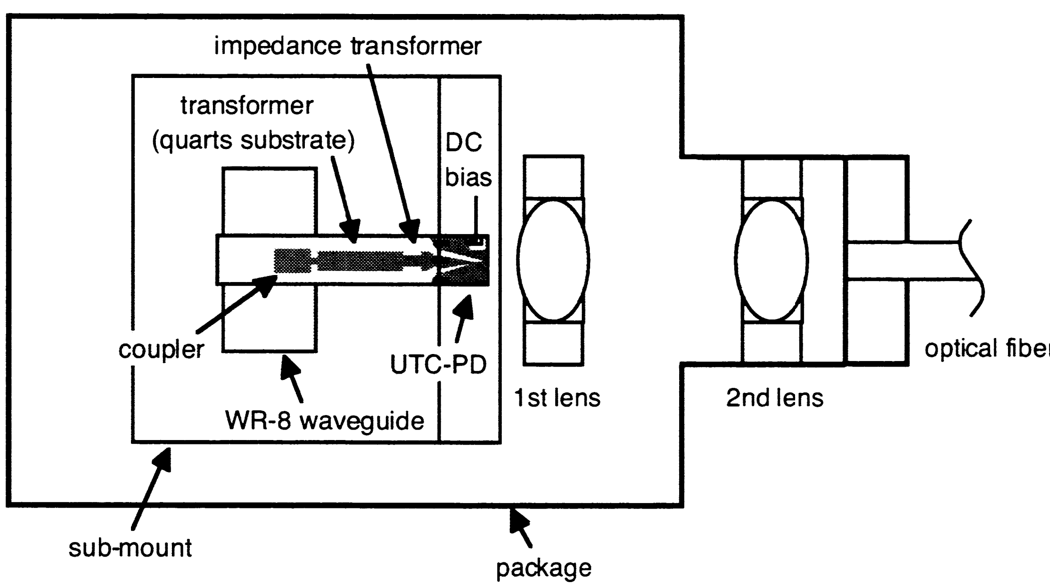


Fig. 2. Schematic drawing of the module configuration.

*B. Module*

To maintain good fabrication yield and performance reproducibility, the module should be compatible with standard electrical/optical assembly technology. We therefore developed a waveguide output UTC-PD module whose size and configuration are equivalent to those of the conventional butterfly-type O/E device module. Figure 2 is a schematic drawing of the module configuration. MSL based transformer was designed and fabricated on a quarts substrate (thickness: 150 μm) to electrically connect the PD to the rectangular waveguide output port with low loss and less frequency dependence. It has an impedance transform circuit (from 50 Ω to 75 Ω) on the PD side, and an MSL-to-rectangular-WG coupler on the other side. Figure 3 shows the return loss of the transformer against frequency calculated by using a three-dimensional numerical simulator (High Frequency Structure Simulator; HFSS). Here, the size of the coupler and the back-short depth were chosen to be 390 μm × 220 μm and 640 μm, respectively, as optimum values. As seen in this figure, the return loss is successfully suppressed to less than -10 dB in the entire frequency range in the F-Band, and the transmittance of this transformer has nearly flat frequency dependence and is larger than -0.5 dB in the F-Band. The transformer connecting the UTC-PD and the WR-8 waveguide was placed in a trench (width × height = 0.6 × 0.5 mm) on a sub-mount, and the UTC-PD chip was electrically connected to the quartz transformer using gold ribbons. A DC bias pad was also electrically connected to the DC-bias port on the side of the package through a series resistor (50 Ω) and a parallel capacitor (2.2 nF) to protect the PD from external electrical surges. Then, a fixed back-short, which eliminates mechanical tuning, was placed on the sub-mount. Thus, the output signal goes to the bottom side of the sub-mount shown in Fig. 2. Finally, the photodiode was optically coupled to the optical fiber using a two-lens system, and these optical parts were welded onto the package using an automated YAG laser welder. This assembly technique provides highly stable optical alignment between the photodiode and optical fiber. The entire fabrication sequence is quite similar to that of the conventional O/E device module, so that standard assembly/testing equipment can be used. The optical beam was slightly defocused on the device, so that the effective responsivity became about 0.35 A/W.

Figure 4 is a photograph of the fabricated module connected to the WR-8 waveguide. The module size is 12.7 mm × 30 mm × 10 mm, excluding the optical fiber. The rectangular waveguide output port is located on the bottom side of the module and connected to a standard F-3922/67B-008 flange using a miniaturized waveguide extension. A miniature SMC connector was used as the DC bias port.

*C. Characterization*

The mm-wave output characteristics of the fabricated module were measured using a power meter (DORADO, DS-28-6A). For the output power characterization, pulse trains from an actively mode-locked laser diode operating at 60 GHz were optically multiplexed by using an arrayed waveguide grating [12] to prepare quasi-sinusoidal 120-GHz mm-wave light signal ($\lambda$ = 1.55 μm, FWHM: 1.5 ps). For the measurement of frequency characteristics, the optical sinusoidal signal was prepared by two-mode beating using two wavelength-tunable laser-diodes ($\lambda \approx$ 1.55 μm) so that the mm-wave frequency could be changed in a very wide range. The optical modulation index of this signal was close to unity.

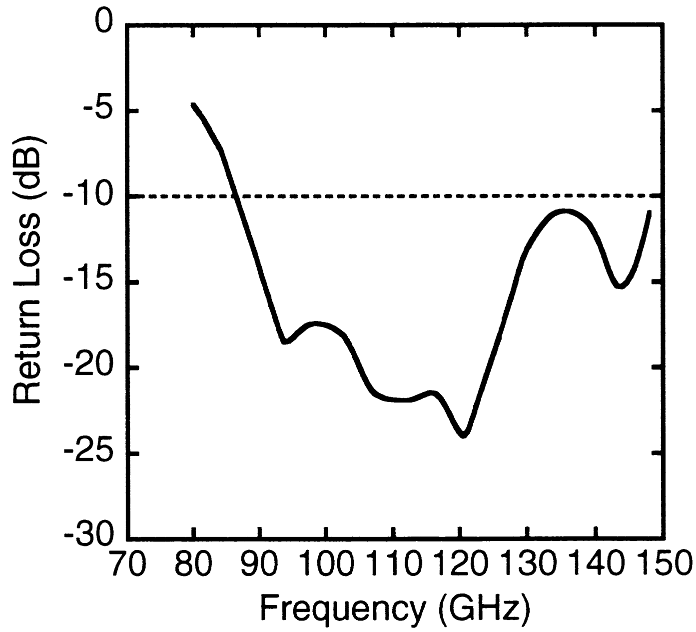


Fig. 3. Calculated return loss of the transformer.

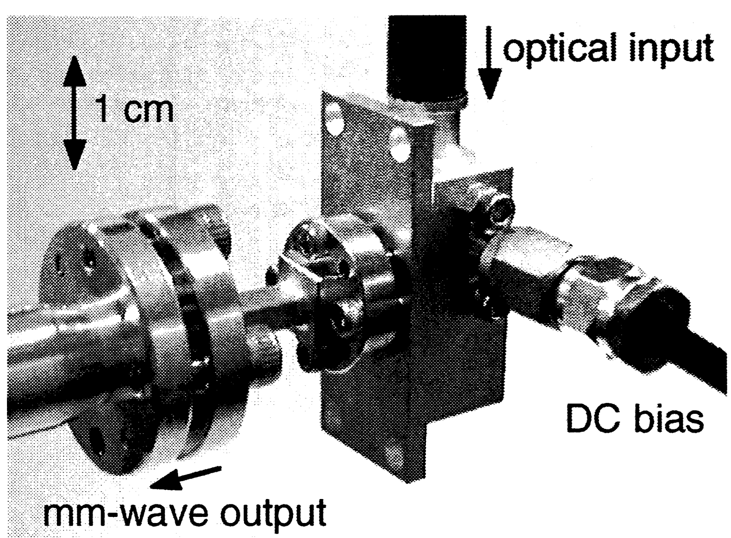


Fig. 4. Photograph of the waveguide-output URC-PD connected to the WR-8 waveguide port.

**Experimental Results**

Figure 5 shows the relationship between measured mm-wave output power and diode photocurrent for the fabricated module at a frequency of 120 GHz. Here, the input optical power was changed. A wide linearity is maintained up to a very high mm-wave output power of over 10 mW. The saturation point of the output power increased with increasing bias voltage, and the maximum output power of 17 mW (at a photocurrent of 25 mA) was obtained at a bias voltage of -3 V. To our knowledge, this is the highest mm-wave output power directly generated from a PD module in the F-band. The variation of the maximum output power against bias voltage is attributed to both the shift in the operating voltage along the load line and the space-charge effect in the collection layer [5].

Figure 6 shows the relative output power against frequency for a photocurrent of 10 mA. The output 3-dB down bandwidth was about 55 GHz, which fully covers the F-band. The solid curve in the figure is a fitting calculation based on an analytical model of the matching circuit. The experimental result agrees well with the calculation, indicating that most of the frequency variation is that of the integrated matching circuit, and thus the frequency variation of the transformer is considered to be reasonably flat in the measured range. In addition, the steep decrease of the output power at the low-frequency side is due to the cut-off characteristics of the WR-8 waveguide (at 73.8 GHz), which were not included in the calculation. In the high-frequency region, on the other hand, the output power does not decrease steeply with increasing frequency. This is because higher-order-mode output is possible in the frequency region above 147.6 GHz. Thus, the fabricated module can cover the required frequency range for ALMA (from about 80 to 160 GHz [2]) by itself.

Figure 7 summarizes the reported maximum RF output powers against the operation frequency for UTC-PDs [7,8,13-16] and conventional pin-PDs [6,17-19]. The difference between the two types of devices becomes larger as the frequency increases, and the output power of the UTC-PDs becomes about two orders of magnitude larger at around 120 GHz, reflecting their much higher saturation current level. These results clearly demonstrate that the UTC-PD is a promising device for generating high-power mm-wave signals without electrical power amplifiers. Moreover, the output power from the UTC-PD module in this study is comparable to those obtained by the UTC-PD chips. This implies that the transformer connecting the UTC-PD to the rectangular waveguide has a low transmission loss.

For the practical use, long-term stability is also an important issue. Although bias-temperature and optical-input stress tests have confirmed that UTC-PDs designed for 40 Gbit/s optical communication systems have excellent reliability [20], we also measured the variation of dark current in the fabricated waveguide-output module under optical input stresses at room temperature (Fig. 8). Here, the module designed for the operation in the W-band [8] was used. The internal configuration of this module is identical to the one for the F-band. The module was biased at -2 V with an optical input corresponding to a photocurrent of 10 mA (responsivity is about 0.35 A/W). Except for the initial increase, the dark current stays at a very low level for more than 3000 hours. These values are considerably lower than the generally required level for high-speed PDs of 1 μA. This indicates that the fabricated UTC-PD chip is reasonably reliable. The changes in responsivity and mm-wave output power at the same photocurrent were also confirmed to be very small after this long-term stability test. These results indicate that the optical alignment by YAG laser welding as well as the device parameters, such as series resistance and junction capacitance, are quite stable.

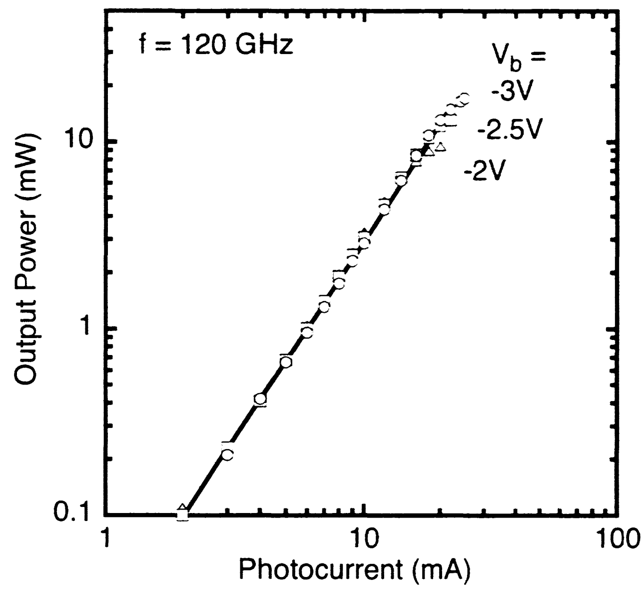


Fig. 5. Relationships between the measured mm-wave output power and diode photocurrent at 120 GHz for several bias voltages.

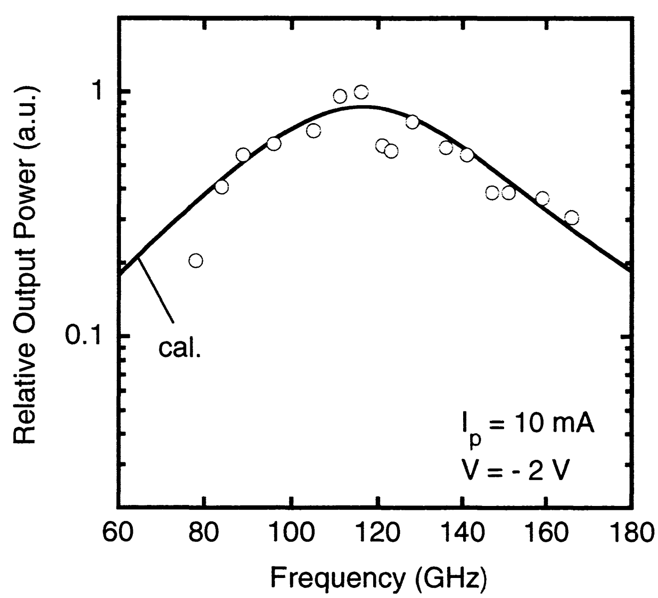


Fig. 6. Relative output powers from the module against frequency. The solid curve in the figure is a calculation based on an analytical model.

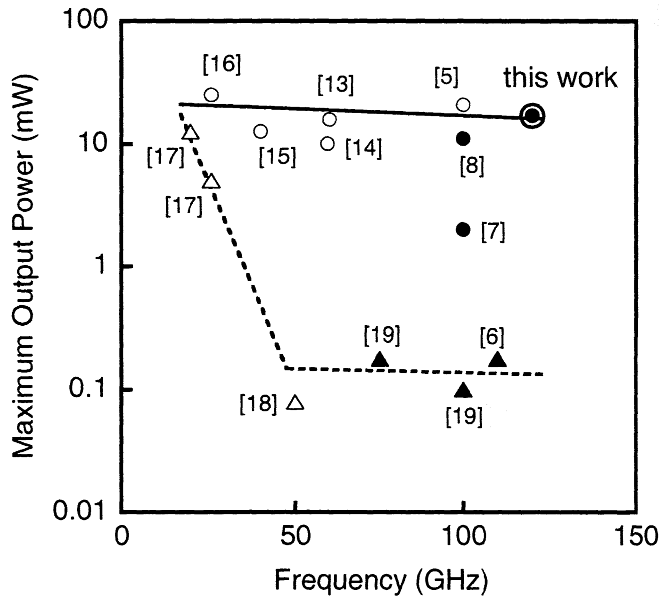


Fig. 7. Comparison of reported mm-wave output power against the operation frequency for UTC-PDs and pin-PDs. Circles are for UTC-PDs and triangles for pin-PDs. Open marks are for chips, and closed ones for modules. Numbers in the figure correspond to the references.

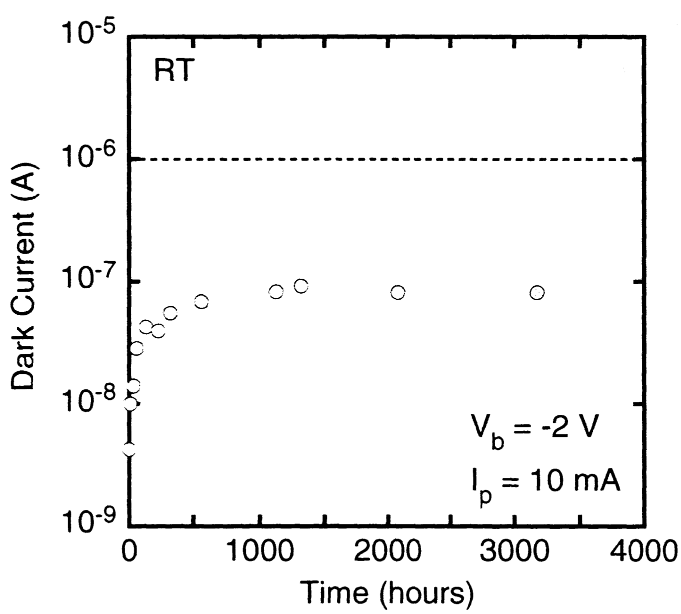


Fig. 8. Variation of the dark current against time under optical input and reverse bias stresses.

**Summary**

We have designed and fabricated a uni-traveling-carrier photodiode module having a rectangular waveguide output port for operation in the F-band. The module is designed to be compatible with standard assembly technology. It exhibits a record maximum saturation output-power of 17 mW at 120 GHz, and a 3-dB bandwidth as wide as 55 GHz, which fully covers the F-band. The stability of the module was also characterized under an optical input stress (photocurrent = 10 mA). It was found that the dark current stays at a sufficiently low level for more than 3000 hours, and the mm-wave output power does not change during that time. These results clearly demonstrate that the waveguide-output UTC-PD module is highly promising for use as a high-power photonic mm-wave generator in a photonic local oscillator system in radio telescopes, such as ALMA.

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