ALMA Memo #396:
A Photonic MM-Wave Reference and Local Oscillator Source.

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Abstract

We report further progress on the development of a photonic mm-wave waveguide source suitable for application as a phase reference and as a local oscillator. The mm-wave power was generated in a W-band waveguide mount by the beating of two 1.55 µm laser beams in a modified commercial photodiode. Maximum optical to mm-wave power conversion efficiency of 1.8% was measured at 75 GHz, where an input power of +10 dBm yielded a non-saturated output power of –7.5 dBm. Measured output powers fell approximately as frequency^{-4} above 100 GHz, decreasing from about –10 dBm at 100 GHz to –40 dBm at 625 GHz. We remark that the mount is non-optimised for frequencies above 110 GHz, and so these measurements represent a lower limit on the available power.

I: Introduction

Previous memos in this series [1, 2] have already discussed photonic sources of mm-wave radiation suitable for providing the phase reference and as a local oscillator for ALMA. These devices generate power at the difference frequency of two near infrared laser beams by using ultrafast photodiodes. We have extended previous measurements on commercial photodiodes [2] by incorporating modified devices into a waveguide mount. Advantages of this approach include the ability to provide optimised photodiode-embedding circuit impedance match conditions, e.g. by the use of stub tuners, and the ease of interface with standard waveguide components. The stub tuner approach is particularly useful in the case of photodiode mm-wave sources, as the effects of large and sometimes uncertain capacitance on the high frequency roll-off of the responsivity can be reduced.

We describe how the 1.55 µm wavelength photodiodes [3] were adapted for use in the specially designed W-band waveguide mount. We further report how the cleaved single mode optical fibre was fixed in position with respect to the photodiode chip to form a compact and mechanically stable mm-wave source. Results are presented showing the dependence of mm-wave power on optical input power and on applied bias. Although the mount is optimised for W-band frequencies, i.e. from 75 GHz to 110 GHz, and the diode bandwidth is below 100 GHz, we have been able to measure powers up to the optical source imposed limit of 625 GHz. Finally, we demonstrate the reproducibility of the design by comparing the W-band characteristics of two photomixers for fixed tuning. These results extend previous measurements made at frequencies up to 170 GHz on an earlier version of the waveguide photomixer [4].

II: The photomixing source and apparatus

The pin photodiodes utilised are epitaxially grown on InP and are supplied [5] as chips 2 mm in length and 500 µm in width. Incident 1.55 µm radiation is injected through an antireflection-coated facet via a rib waveguide to the 5 µm x 20 µm photodiode. The photodiode output contact is connected to the centre conductor of a short length of 50 Ω coplanar waveguide. Manufacturer's data indicates an external DC responsivity of 0.3 A/W at a reverse bias of 1V with a bandwidth of 70 GHz in a 50 Ω environment [3].

Our waveguide photomixer approach requires that the photodiode chip be incorporated into a metal enclosure or channel. The supplied photodiode substrate is relatively large compared to the operational wavelength and longitudinal propagation of mm-wave radiation in a waveguide mode may occur for frequencies above 94 GHz. Propagation of such a mode in the channel would represent a loss of power from the desired TE_{10} mode in the WR-10 output waveguide. To address this problem the chips were mechanically thinned to 200 µm and reduced in width to 380 µm: this modification increases the cut-off frequency of the undesired mode to 145 GHz.

A modified chip, appearing as the predominantly black area on the right of Fig. 1, was fixed in the channel of a photomixer block. The central rectangular area in

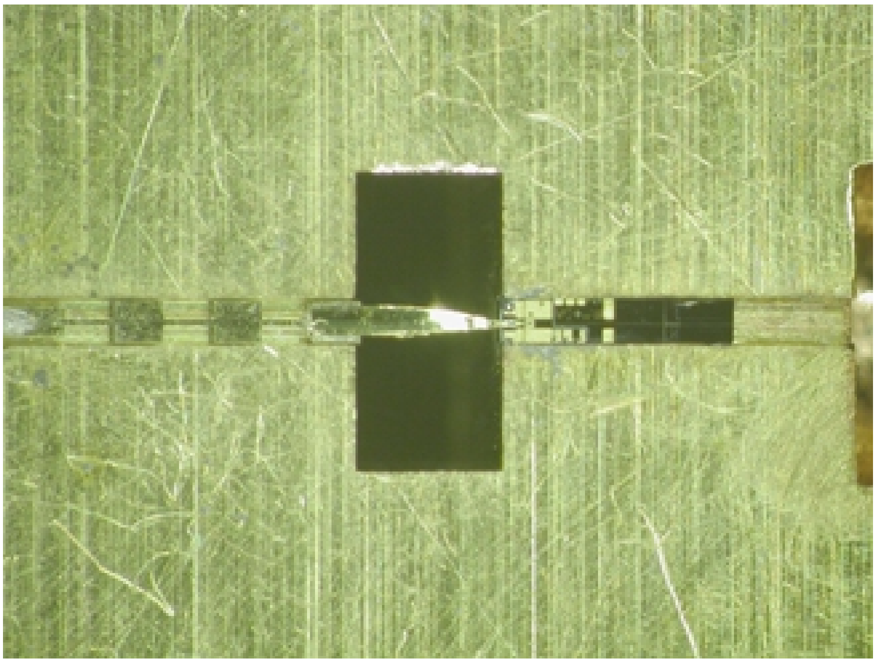

Fig. 1: Photograph of u^{2}t photodiode chip (right centre) incorporated in a photonic mixer block.

the figure is the WR-10 waveguide. Constant voltage bias is applied by means of a radio frequency choke structure defined on a 200 µm thick quartz substrate. This is visible on the left hand side of Fig.1. A wedge shaped gold foil extends across the WR-10 waveguide to make contact with the output line on the photodiode chip. The electrical connection between the photodiode contacts and the foil probe is made by means of low melting point InSn solder.

A cleaved single mode optical fibre transports the 1.55 µm radiation to the photomixer. The stripped fibre enters the photodiode channel from the right-hand side as viewed in Fig. 1 and its end is positioned about 40 µm from the chip facet. The fibre is glued into a stainless steel ferrule, which passes through a hole in the block and is then clamped to an x-y-z positioner. When alignment between fibre and chip has been optimised, the ferrule is fastened to the photomixer block by epoxy resin. After this has cured, the strength of the bond is such that light finger pressure on the exposed ferrule does not disturb the fibre to chip alignment.

In use, the photomixer block is capped with a metal lid through which the rectangular waveguide continues. A sliding backshort in this waveguide may be adjusted by means of a micrometer screw: Fig 2. To give an idea of scale, the rectangular block dimensions are 20 mm x 22 mm x 7 mm. The micrometer adjustment mechanism for the backshort could be eliminated in a future fixed backshort production device, considerable reducing the source height. This figure also shows the SMA bias connector and the epoxied stainless steel ferrule that supports the fibre.

Optical power is provided by two 1.55 µm diode lasers whose outputs are combined into a single mode fibre. The lasers and associated microprocessor driven control electronics have been packaged into a single microprocessor controlled 19” rack unit by NRAO: Fig. 3. Frequency offsets from 1 GHz to 625 GHz and a combined output power above +10 dBm is available.

Methods used to characterise the generated mm-wave power depended on the frequency. An external W-band mixer connected to a spectrum analyser was used for frequencies from 75 GHz to 200 GHz. Measured in-band powers were verified to within 1 dB by means of a thermocouple power meter. At higher frequencies the radiation was coupled into free space by a rectangular feedhorn antenna. For power measurement the radiation was focussed into a calibrated Golay cell by a HDPE lens. Alternatively the mm-wave signal was coupled into a Fourier transform spectrometer for frequency verification.

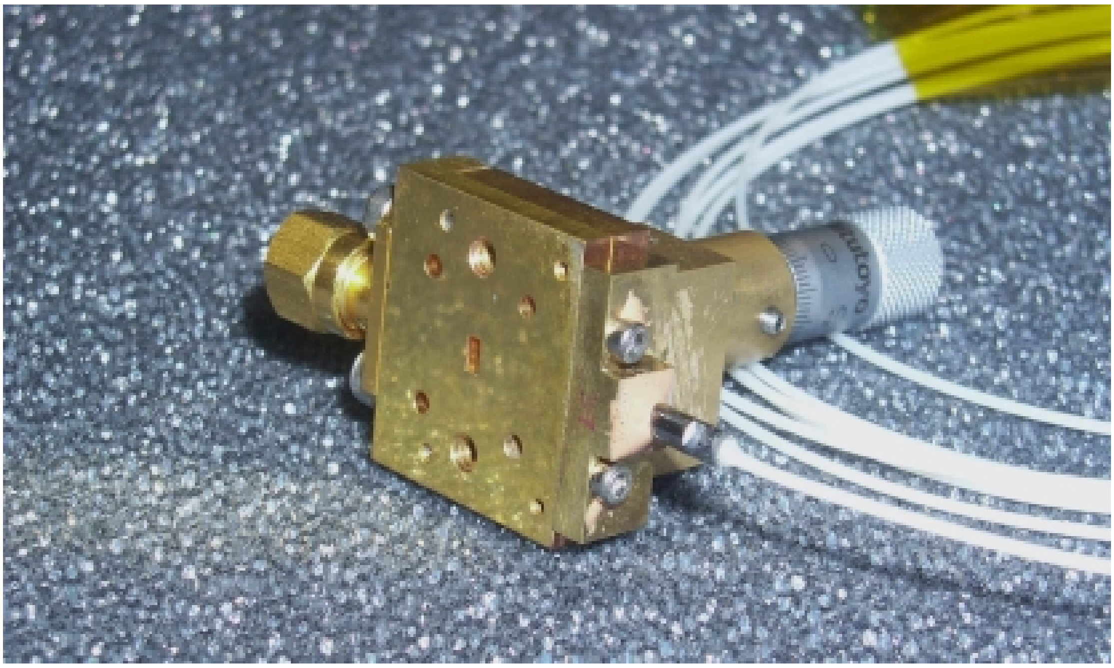

Fig. 2: Photograph of completed photonic sources showing theWR-10 output waveguide and the stainless steel fibre ferrule cemented to the block. The block base dimensions are 20 mm x 25 mm.

Fig. 3: Photograph of the front panel of the NRAO dual 1.55 µm laser source. A keypad allows the user to set a difference frequency in the range from 1 GHz to 625 GHz

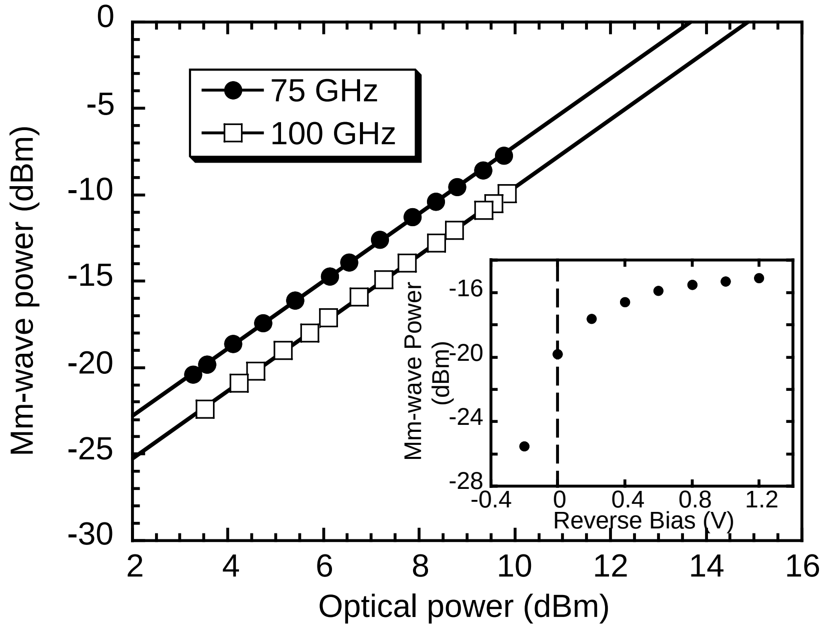

Fig. 4: Dependence of mm-wave power on optical power at frequencies of 75 GHz (solid circles) and 100 GHz (open squares) for a reverse bias of –1.2 V. The lines indicate a slope of two. The inset shows the dependence of the mm-wave power on bias at a frequency of 100 GHz and an optical power of +7.8 dBm.

III: Experimental results and discussion

The DC external responsivity of the photodiode was measured as 0.4 A/W for a reverse bias of 1.2 V, in good agreement with the manufacturer's specification. Figure 4 presents the dependence of the mm-wave power on optical power at frequencies of 75 GHz and 100 GHz for a reverse bias of –1.2 V. In both cases the expected square law response is observed, as indicated by the lines which have a slope of two. Respective maximum mm-wave powers of –7.7 dBm and –10 dBm are obtained for the maximum excitation power of +10 dBm. These values correspond to a power conversion efficiency ≥ 1%. The data shows no evidence of saturation and so mm-wave powers of at least 0 dBm would be expected if this behaviour continues to the safe operating power of +16 dBm. For comparison purposes, powers of +10 dBm have recently been generated by strongly saturated uni-travelling-carrier photodiodes [6] driven by mode locked laser pulses. The pulse repetition frequency was 100 GHz and the average photocurrent was about 30 mA.

The bias dependence of the power at 100 GHz is shown in the Fig. 4 inset for an optical power of +8 dBm. The signal initially increases strongly as the bias is changed from forward to reverse, and the power then saturates for reverse biases above 0.5 V. The total contrast available by varying the bias by 1.4 V is about 10 dB. Decreasing reverse bias increases the junction capacitance and possibly also increases the carrier transit time. Both these effects reduce the overall detector bandwidth – see below - and hence the mm-wave power at a given frequency decreases. This bias sensitivity offers the facility to remotely control photomixer output powers, a useful feature if the photomixer is to be used as a local oscillator for SIS mixers.

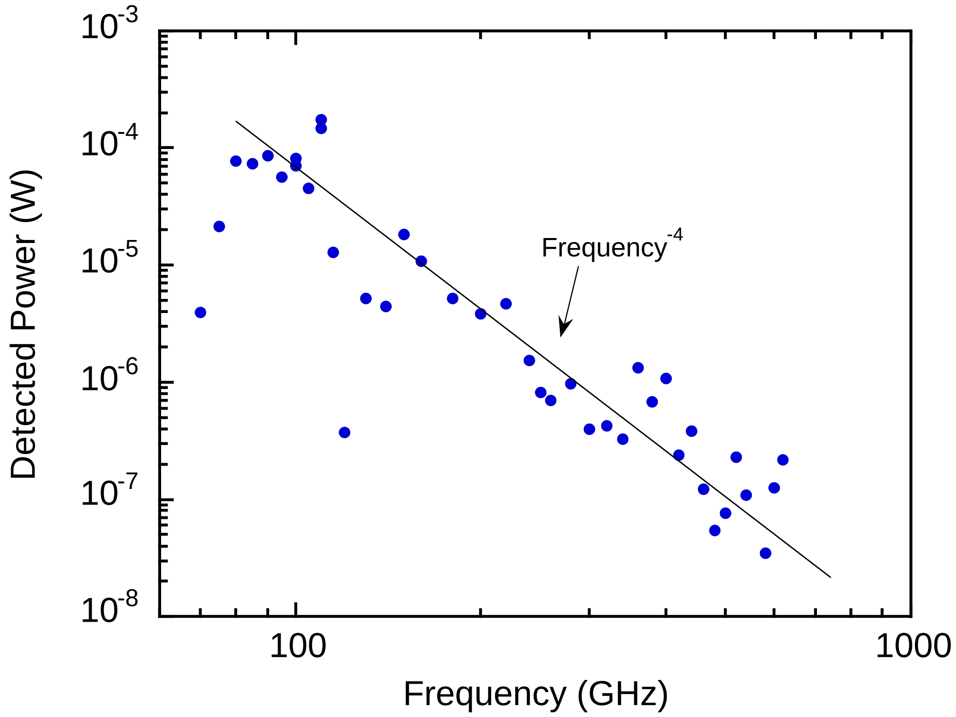

Fig. 5: Dependence of mm-wave power on frequency for a constant excitation power of +10 dBm. The line is a guide to the eye and indicates a frequency^{-4} dependence

While measuring the above power dependences, the positions of the backshorts were optimised at each frequency. Fig. 5 displays the dependence of this maximised power as a function of frequency between 75 GHz and 625 GHz. The measurements were made at a reverse bias of 1 V and for a constant +10 dBm optical input power. The mm-wave power is found to peak at around –10 dBm for frequencies close to 100 GHz. A sharp dip is observed in the region of 120 GHz, above which the power recovers and then decreases approximately proportional to (frequency)$^{-4}$ so that the detected power above 600 GHz is about –40 dBm.

The frequency response of the photomixer is determined by both photodiode properties and by the characteristics of the photomixer block and coupling structure. The photodiode bandwidth is a combination of the RC bandwidth (100 GHz) and the carrier transit time limited bandwidth (110 GHz) [3]. The latter is an intrinsic limit imposed by the photodiode design and materials. Within the band of the photomixer block, 75 GHz to 110 GHz, the effects of capacitance on the roll-off with frequency can be reduced by tuning the backshort appropriately. This tuning become less effective as the frequency rises and the waveguide becomes overmoded. HFSS calculations show that radiation can propagate in the photodiode and choke channels for frequencies above 150 GHz: this is a potential further loss mechanism. In addition the feedhorn beam pattern is unknown at high frequencies and the efficiency of coupling generated power to the Golay cell detector may therefore be lower. All these factors are tend to reduce the detected power and thus the data displayed in Fig. 5 actually represents a lower limit on the available mm-wave power. We note that a power above –30 dBm is available at frequencies up to 300 GHz. This power level demonstrates the suitability of this non-optimised photomixer, when driven by an appropriately phase locked laser system, as a local oscillator source for an SIS mixer up to 300 GHz.

We mention that the sharp dip in the spectrum at about 120 GHz is probably a consequence of placing the photodiode close to the waveguide wall and contacting to it by means of a probe extending across the guide. The equivalent circuit of this geometrical arrangement is a series LC combination in parallel with the photodiode [7]. This LC circuit has a short circuit resonance in full height waveguide at approximately twice the cut-off frequency of the TE_{10} mode. For our WR-10 waveguide the cut-off frequency is about 59 GHz, and thus the dip position is consistent with this explanation. This undesirable drop in output power can be eliminated by either reducing the height of the waveguide [7] or by positioning the source centrally in the waveguide [8].

Finally, to demonstrate the reproducibility of our design, we compare the performance of two photomixers: Fig 6. This graph shows the performance of the two sources for a fixed backshort tuning which maximised the 90 GHz power. One photomixer (red squares) was driven by the University of Kent laser system [4] and the second (blue circles) was used in the study with the NRAO source described above. The output spectra are similar in shape over most of the waveguide band, although some discrepancy can be seen above 100 GHz. Output powers from the first mixer have been scaled by a few dB to achieve a better overlap of the curves. The discrepancy between curves is not surprising given differences between the laser systems, the responsivities of photodiodes and the manual assembly methods used to shape the probe, assemble the devices and position the fibre. We envisage that a production photomixer would incorporate a photolithographically defined probe on a quartz substrate which would present an impedance matched load to the photodiode. This should considerably assist in the production of photomixers with similar performances and with a lower in-band frequency dependence.

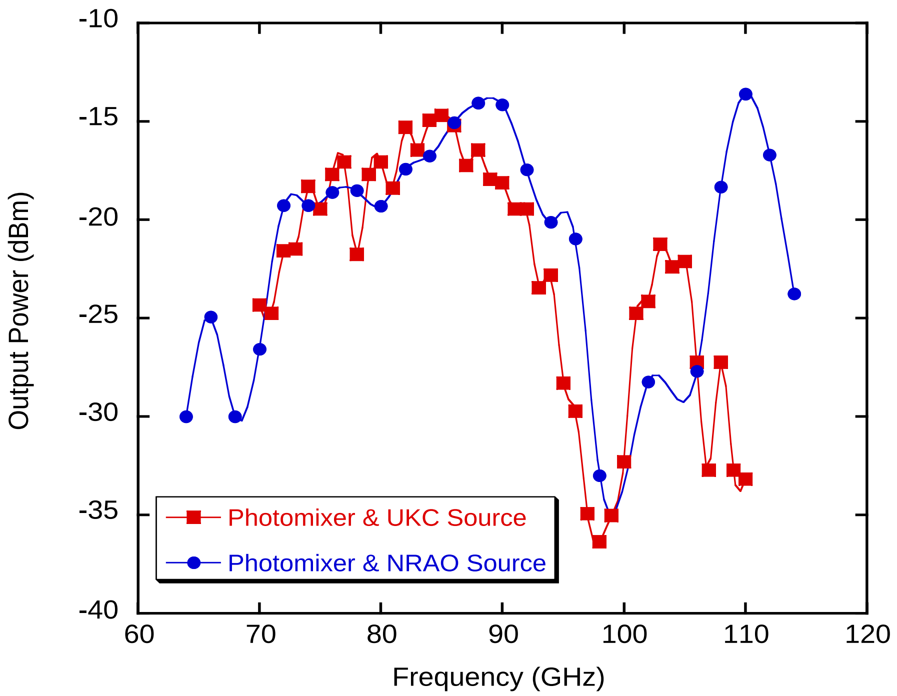

Fig. 6: Comparison of the W-band tuning of two photomixers, both of which were fixed tuned for optimum power at 90 GHz. For comparison purposes the red data points have been scaled by a few dB to better overlap the blue points. The curves are a guide to the eye.

IV: Conclusion

Ultrafast photodiodes have been coupled to rectangular W-band waveguide in a specialised mounting incorporating a tuneable backshort. Non-saturated peak powers above –8 dBm (-10 dBm) were generated at frequencies of 75 GHz (100 GHz) with power conversion efficiencies above 1%. The reproducibility of our design has been confirmed by comparing the performance of two fixed tuned devices. Output powers resulting from optimised tuning were found to decrease strongly with increasing frequency, dropping from about –10 dBm at 100 GHz to a level of –40 dBm at 625 GHz. The trend of the data indicates that the power depends approximately on frequency^{-4}. Although the mount is not optimised for frequencies in the 200 GHz to 300 GHz range, we believe that the –30 dBm of power detected is already sufficient for the device to be used as a LO source for an SIS mixer.

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