ALMA memo 435

A Hybrid Option for the First LOs using Direct Photonic LO Driver

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Abstract

We propose a hybrid option for the first local oscillators (LOs) of ALMA in which a direct photonic LO driver is used to drive cold multipliers. The photomixer using NTT uni-travelling carrier photodiode has been demonstrated to have high power of 2 m W at 100 GHz and low amplitude noise of $< 7 - 17$ K/μW in the frequency range of $98 - 105$ GHz. This option simplifies the LO part of the cartridge in the baseline ALMA and retains a future possibility for a direct photonic option.

1 Introduction

The current baseline design of the first LO system in baseline ALMA is composed of "warm multiplier assembly"(WMA) operating at room temperature for all frequency bands and "cold multiplier assembly"(CMA) operating at cryogenic temperature for bands 4 through 10 [1]. The WMA is a VCO assembly of YIG tuned oscillator (YTO) followed by an active multiplier chain (AMC) with a power amplifier. The VCO is phase-locked to the signal generated in a photomixer by mixing two laser signals sent in a long optical fiber. This system is called as "photonic reference". Another system called "direct photonic LO" has been investigated to be applied in ALMA [2]. If the photomixer can generate enough power to drive SIS mixers at submillimeter wavelengths and has a low noise performance as specified in the project book, the direct photonic approach is the best option for ALMA because of its simplicity compared with the photonic reference option.

In Japan, a joint research group of NAOJ and NTT Laboratories has succeeded in developing a high power W-band photomixer using a uni-traveling-carrier photodiode (UTC-PD) [3]. The direct photonic LO driver with a UTC-PD photomixer used for an SIS mixer at 100 GHz demonstrated that the amplitude noise of photonic LO can be reduced to that of Gunn diode oscillator [4]. The recent experiment of the photomixer that uses a log-periodic antenna and a UTC-PD shows that at least 7 μW is available at 800 GHz [5]. Thus, prospect for direct photonic LO up to band 7 ($275 - 370$ GHz) is very high. However, the specification goal of 100 μW for bands 8 through 10 seems difficult at this moment.

To make the best use of direct photonic LO and to solve the difficulty in getting the required power at submillimeter wavelengths, we propose a "hybrid option" for the first LOs using direct photonic LO driver (DPD) instead of the WMA. This approach could make the first LO system very simple and would facilitate the future extension to the direct photonic LO for all frequency bands.

2 Photomixer with UTC-PD

2.1 High Power Performance

NAOJ and NTT have developed a W-band photomixer using a UTC-PD [3]. The UTC-PD is sensitive to the light covering a wavelength of 1.55 μm and has a higher saturation output with maintaining fast response than other types of photodiode, e.g. Si-PIN, InGaAs-PIN photodiodes [6]. For example, a W-band photomixer using a commercial PIN photodiode has output power of around -13 dBm at 95 GHz [7]. Photo-generated holes in this photodiode do not dominate the response speed due to the collective motion of majority holes in the absorption layer, and only electrons play as active carriers. Therefore, it has a fast response compared with a conventional PIN photodiode. The UTC-PD, which has a p-type photo-absorption layer and a wide-gap electron-collection layer. Recently, Ito et al. [8] reported a pulse response for the UTC-PD of 0.97 ps (FWHM), which corresponds to a 3-dB down bandwidth of 310 GHz.

A UTC-PD is fabricated on an InP substrate with DC and RF signal lines, and the chip is mounted upside down on a fused quartz substrate. @The substrate is then placed across a micro-strip channel and a quarter-height WR-10 waveguide. A simple cross shaped microstrip waveguide transition formed on the quartz substrate is designed to couple the output power into the waveguide [9]. A return loss between micro-strip channel and quarter-height waveguide is calculated to be about -15 dB for the frequency range of $75 - 110$ GHz with High Frequency Structure Simulator (Agilent technologies: HFSS). In designing the RF circuit, the UTC-PD was modeled to have a current source with a parallel capacitor ($20-30$ pF) and a series resistance. An effective load resistance value for the UTC-PD was chosen to be 25 Ω. The UTC-PD is coupled with a tapered strip-line transition which transforms an output impedance of the UTC-PD to 50 Ω. Schematic drawing of the photomixer is shown in Figure 1. The photodiode diameter is 8 μm.

The photomixer is driven by the heterodyne beatnote of the combined output of two distributed feedback (DFB) lasers whose emission wavelengths are around 1.55 μm. The line width

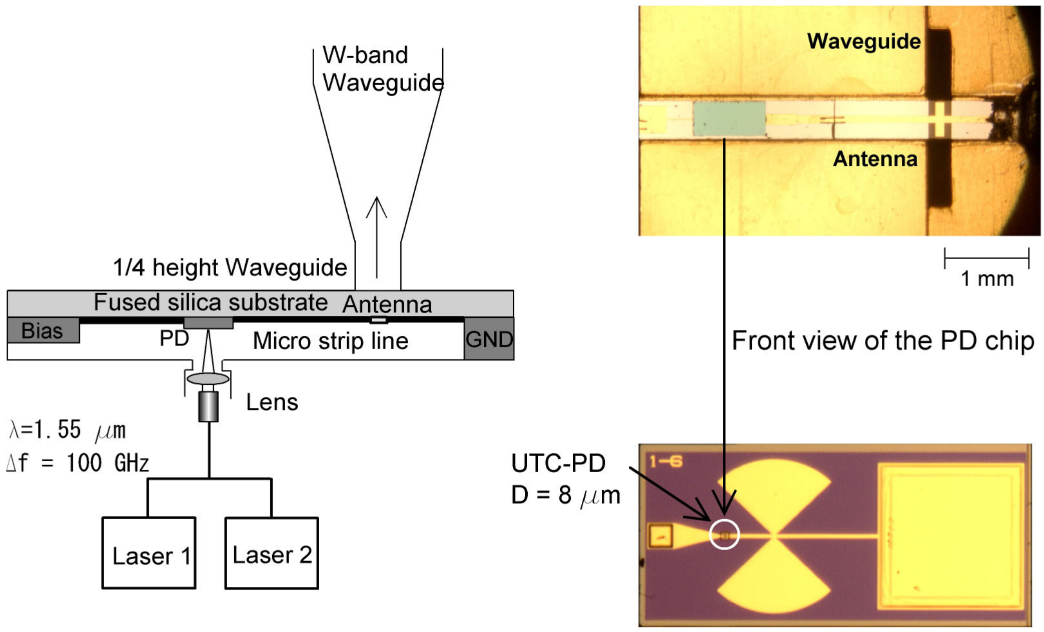


Figure 1: Schematic drawing of a photonic LO and a W-band waveguide photomixer. The waveguide is a quarter-height WR10.

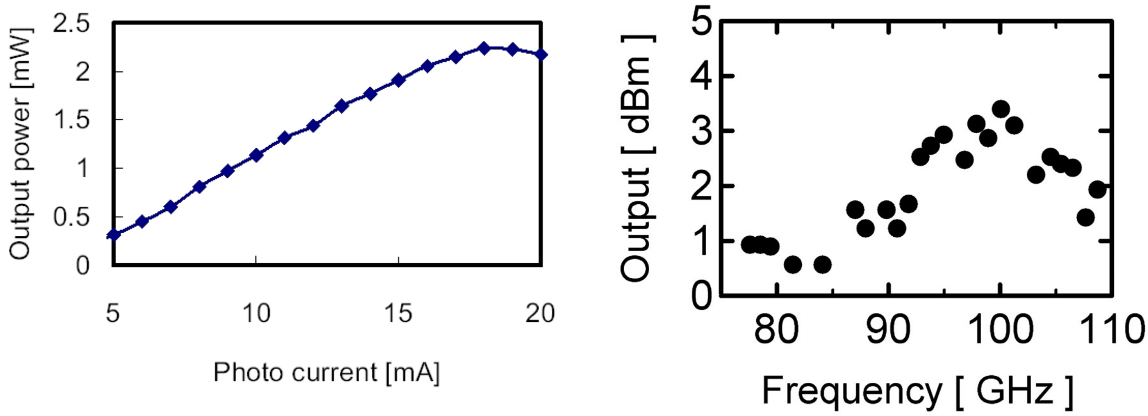


Figure 2: Left: Output power of the W-band photomixer at 100 GHz with changing the photo current. Right: Output power of the W-band photomixer from 75 to 110 GHz. The photo current is 20 mA and an optical power of 200 mW is delivered to the photomixer.

of the lasers is a few hundred kHz in free running operation. Relative intensity noise (RIN) of these lasers is specified to be −155 dBc/Hz. The output of the fiber-coupled DFB lasers, whose total optical power is 20 mW, is amplified up to 200 mW using an Er-doped fiber amplifier (EDFA) with a noise figure of 5 dB. A polarization controller is inserted in an optical path in order to improve contrast of the interference. Output of the fiber coupled semiconductor laser diodes are combined to a single-mode fiber using a 3 dB coupler. The beam from single-mode fiber through relay-lenses of a self-focus and a plano-convex irradiates the UTC-PD. Estimated beam size on the device is about 10 μm in diameter. A relation of photocurrent and output power is shown in Fig. 2.

The output power is also measured by use of calibrated Schottky diode. Calibration of the Schottky diode (Millitech: Waveguide Detector DXP-08-RPFWO) is performed using a backward wave oscillator and a power meter (Dorado: PS-28-6A). The maximum output power is 2.2 ± 0.2 mW at the frequency of 99.8043 GHz. At this point, the photocurrent of the UTC-PD was 20 mA and a reverse bias of 2 V. Saturation of the output power is observed at a photocurrent of around 20 mA. Detected output power may be slightly higher than true output power, because Schottky diode is a broadband detector. Measurements of output power are made over a wide frequency range from 75 to 110 GHz (W-band). The frequency dependence of the output power is shown in Fig. 2. Relative output power variation of the photomixer as a function of frequency is less than 3 dB over the entire range of the W-band without any mechanical tuning commonly used for the Gunn oscillator.

2.2 Low Amplitude Noise Performance

It is expected that the noise of a photonic LO is higher than that of a Gunn diode oscillator, except under the conditions of using very low-noise optical sources and having very high current in the photomixer [10]. Recently, Ueda et al. [4] have demonstrated that amplitude noise of photonic LO can be comparable to that of Gunn diode oscillator. Measured noise temperatures of the SIS receiver driven by the Gunn oscillator and the photonic LO are plotted in Fig. 3. Laser relative intensity noise (RIN) of two DFB lasers is specified to be -155 dBc/Hz. We used an Er-doped fiber laser amplifier with noise figure (NF) of 5 dB. A conversion factor of the photomixer from input optical power to photo current is 0.1 A/W, which includes coupling efficiency of optical fiber to the photodiode and responsivity of the photodiode.

The generated millimeter-wave signal is coupled to the SIS mixer using a WR-8 cross guide coupler with -25 dB ratio. The SIS mixer is composed of two parallely connected twin junctions (PCTJ) which have a mirror symmetrical circuit pattern connected in series [11]. The configuration of the SIS junctions is equivalently two connected in parallel and two in series (Figure 4). The LO power required to drive the SIS mixer is estimated to be $30 - 80$ nW with two simulation methods, one is called as SuperMix[12] and the other is developed at NAOJ.

Both photonic LO and Gunn diode cases show the same noise temperature of around 20 K double-sideband in the frequency range of $96 - 110$ GHz, which corresponds to 4 to 5 times quantum-limited noise performance. The excess noise in the frequency range from 98 to 105 GHz is less than 0.5 K. This means upper limit of $7 - 17$ K/μW for amplitude noise of photonic LO if the amplitude noise of Gunn oscillator is as low as 1 K/μW. However, a slight increase in excess noise of less than 3 K by the photonic LO is observed at 96 and 110 GHz. The cause is still being investigated.

It is interesting to compare the amplitude noise with the predictions by Shillue in ALMA Memo 319 [10]. For laser RIN of -155 dBc/Hz and the optical amplifier with NF $\sim$ 5 dB, the amplitude noise of photonic LO is calculated to be 158 K/μW. This value is not consistent with the measurements. A possibility is that the actual RIN of the laser is much smaller at the beat frequency of 100 GHz than the specified value.

Examples of the current-voltage curves and IF output powers at the LO frequency of 100.6 GHz are also shown in Fig. 3. The upper panel shows a case pumped by the photonic LO and the lower one shows a case pumped by the Gunn oscillator. The current-voltage curve and the IF output power curve of the SIS mixer pumped by the photonic LO are completely in agreement with those of the Gunn oscillator.

Bryerton et al. [13] compared the noise temperature of a 78 GHz SIS receiver when pumped by first by a Gunn oscillator, and then by a YIG LO and driver chain. The additional receiver noise measured using the YIG LO is 5.1 ± 1.2 K. At least, the photonic LO is excellent in respect of amplitude noise compared with YIG and driver chain.

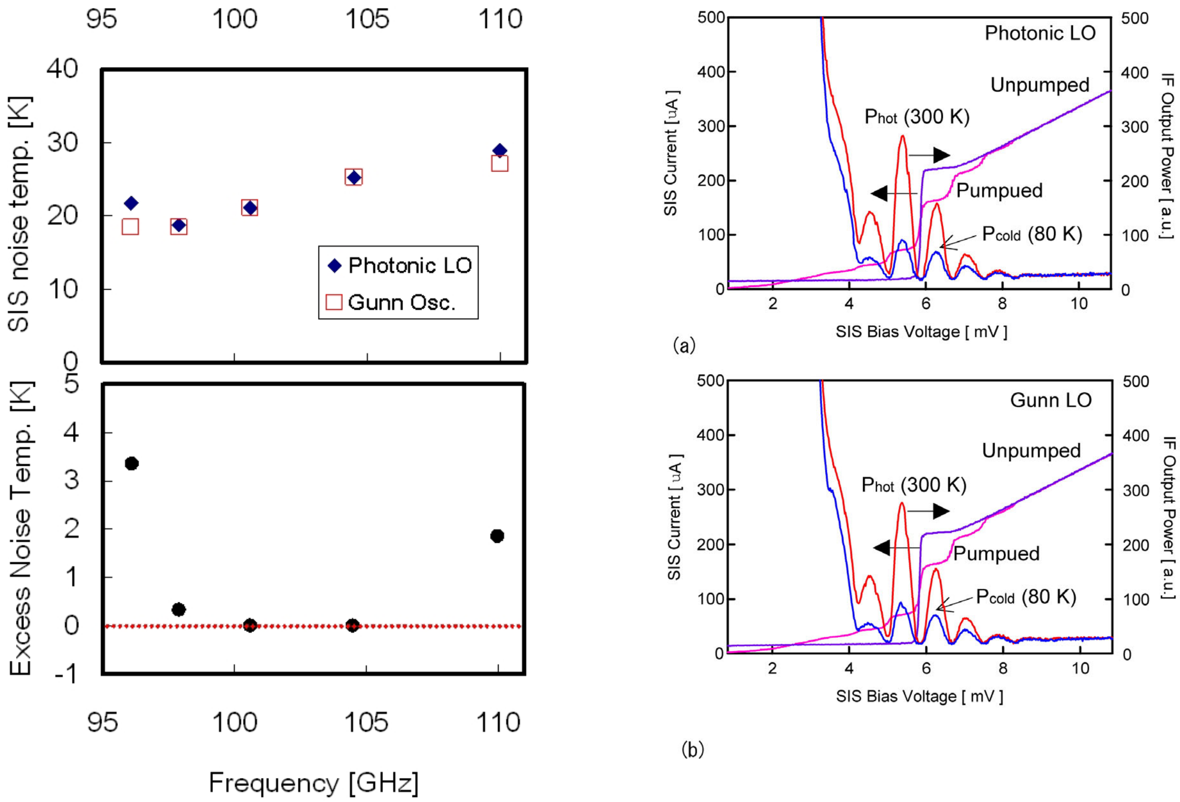


Figure 3: Left: Comparison of SIS noise temperatures pumped by a photonic LO and a Gunn oscillator. Left-lower panel shows difference of the noise temperature between photonic LO and Gunn oscillator. The photomixer is driven by two DFB lasers with RIN of −155 dBc/Hz followed an optical power amplifier with NF of 5 dB and Gain of 10 dB. The photo current is 18 mA and the input optical power is around 200 mW. The absolute accuracy of the SIS noise temperature is ±1.5 K, however, the relative difference of the noise temperature is much lower. The SIS mixer is composed of two PCTJ as shown in Figure 4[11]. Right: The upper panel shows a case pumped by the photonic LO and the lower one shows a case pumped by the Gunn diode oscillator. The current-voltage curve and the IF output power curve of the SIS mixer pumped by the photonic LO are completely in agreement with those of the Gunn diode oscillator.

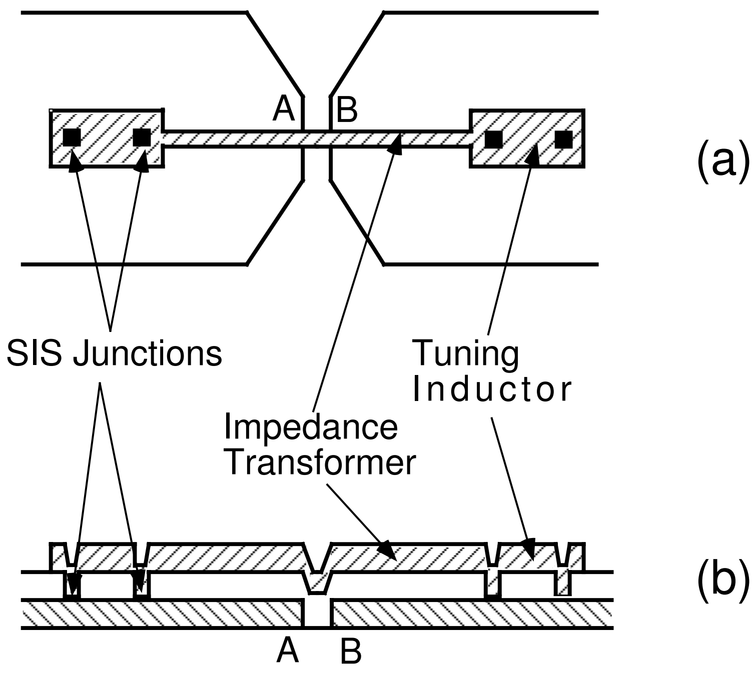


Figure 4: The geometry of two parallely connected twin junctions [11]

3 Direct Photonic Driver as a Replacement of Warm Multiplier Assembly

A direct photonic driver (DPD) can replace a warm multiplier assembly (WMA), which consists of an active multiplier chain (AMC), a YIG tuned oscillator (YTO), and a reference photomixer [1]. A comparison of DPD and WMA is shown in Figure 5. Input of DPD and WMA is a fiber with the same laser signals except for the power level. An optical power amplifier is necessary to amplify the power from a few mW to $\sim$ 100 mW. A power amplifier and cold multipliers following DPD are the same as the baseline scheme. The DPD scheme does affect the development of cold multipliers and power amplifiers.

A block diagram of the DPD scheme for 10 frequency bands is shown in Figure 6. For band 4, we expect that more than 100 μW will be produced by a W-band photomixer in an oversize mode. A commercial photomixer with a coaxial K connector (eg. NEL KEPD2C6E1VD) is available for band 1. For band 3 and band 4, a PIN attenuator is added to optimize LO power to two SIS mixers for dual polarization, while the common power is controlled by bias voltage of the photomixer. For the other bands, the LO power is adjusted by the multiplier bias.

Technical merits of the hybrid option are as follows.

1. Simple and small. Several parts of the WMA can be eliminated. The size of DPD is the same as that of a reference photomixer, so the physical size of the ambient temperature part of a cartridge is significantly reduced.

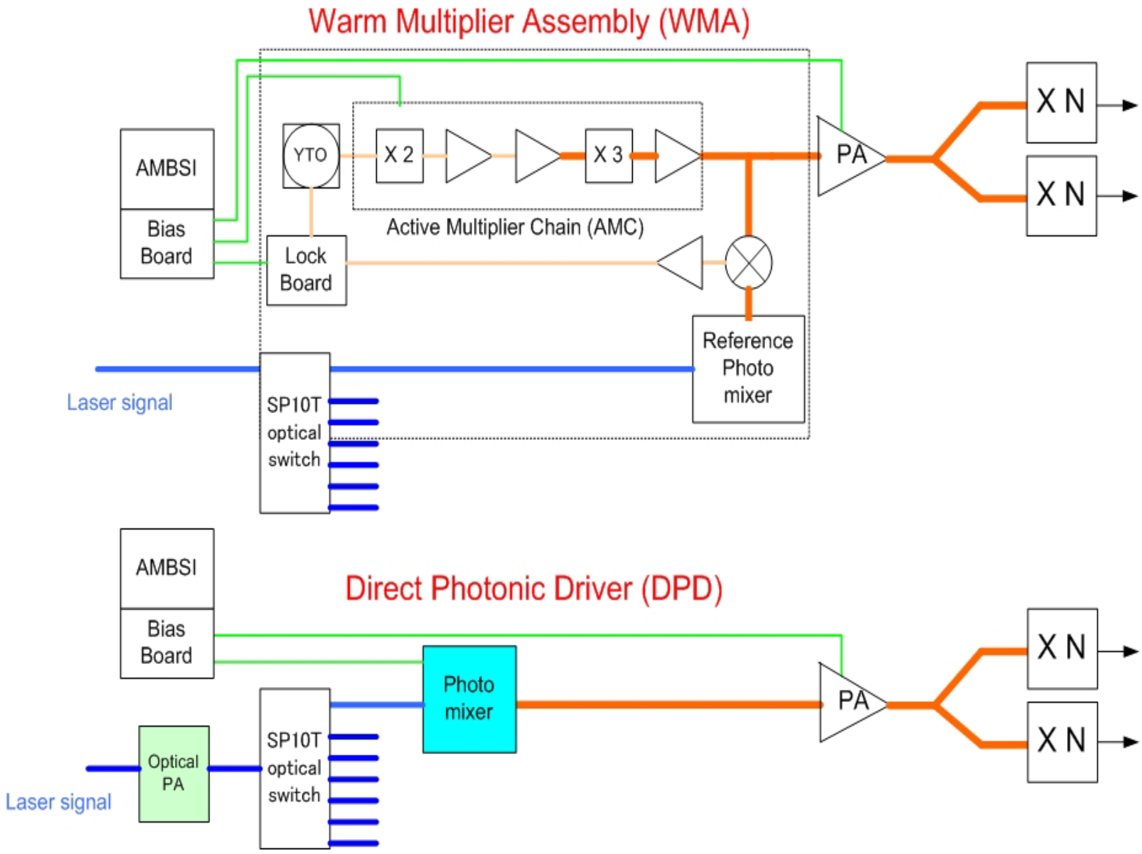


Figure 5: Comparison of the baseline WMA with the direct photomixer driver (DPD) plans.

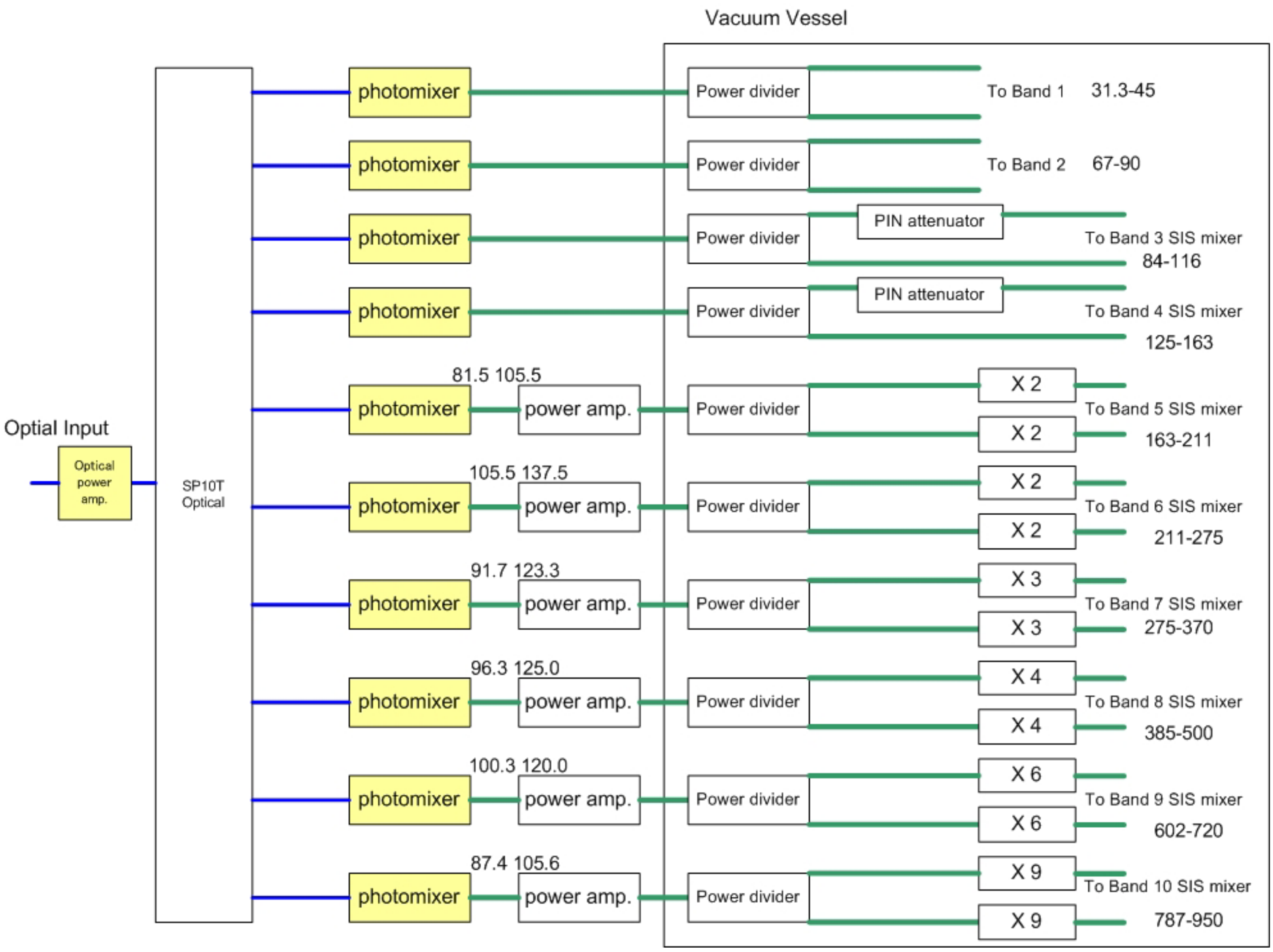


Figure 6: A block diagram for a hybrid option with direct photonic driver (DPD). The numbers show frequencies in GHz.

2. Reduction of cost. The costs of a reference photomixer and a DPD photomixer are similar, and the costs of AMC, W-band mixer, and cross guide coupler are eliminated. On the other hand, an optical power amplifier and a new scheme for phase rotation are necessary. The net effect is expected to be lower cost.

3. Less risk of electromagnetic interference. Three bands are expected to be active simultaneously ("observing", "next scheduled" and "calibration"), and harmonics of the YTO will sometimes fall in an active band. In the DPD scheme, no multiplication is required below 140 GHz.

4. Easy to extend to a direct photonic LO option. This will be discussed in the next section.

The phase noise of DPD option is expected to be the same as that of the WMA option because in both cases it is dominated by the phase noise of the laser synthesizer in the central building. If the phase noise of the WMA option is as low as specified, the phase noise of DPD option is also low.

We have a plan to measure the amplitude noise of a combination of W-band photomixer, W-band power amplifier and multipliers at 450 and 830 GHz with existing SIS receivers at NAOJ. This experiment will reveal the effect of frequency multiplication on the signal-to-noise ratio of the LO output. Though it must be demonstrated experimentally, the amplitude noise of the combination is expected to be low, since the noise of a power amplifier is reported to be enough low [14].

4 Prospect for Direct Photonic LO

The direct photonic LO concept described in [2] is developed in more detail in [1] (section 7.7) and in [19]. It will provide a great benefit to the ALMA LO system if the following requirements are met.

1. Sufficient output power ($> 100\mu$W) to drive SIS mixers up to band 10 ($799 - 938$ GHz)

2. Low amplitude noise comparable to that of Gunn or WMA

3. Low phase noise comparable t o that Gunn or WMA

4. Operation at cryogenic temperature especially for driving submillimeter-wave SIS mixers

A block diagram for direct photonic LO is shown in Figure 7. In this diagram optical power dividers are located outside the vacuum vessel for easy diagnostics of receiver cartridge.

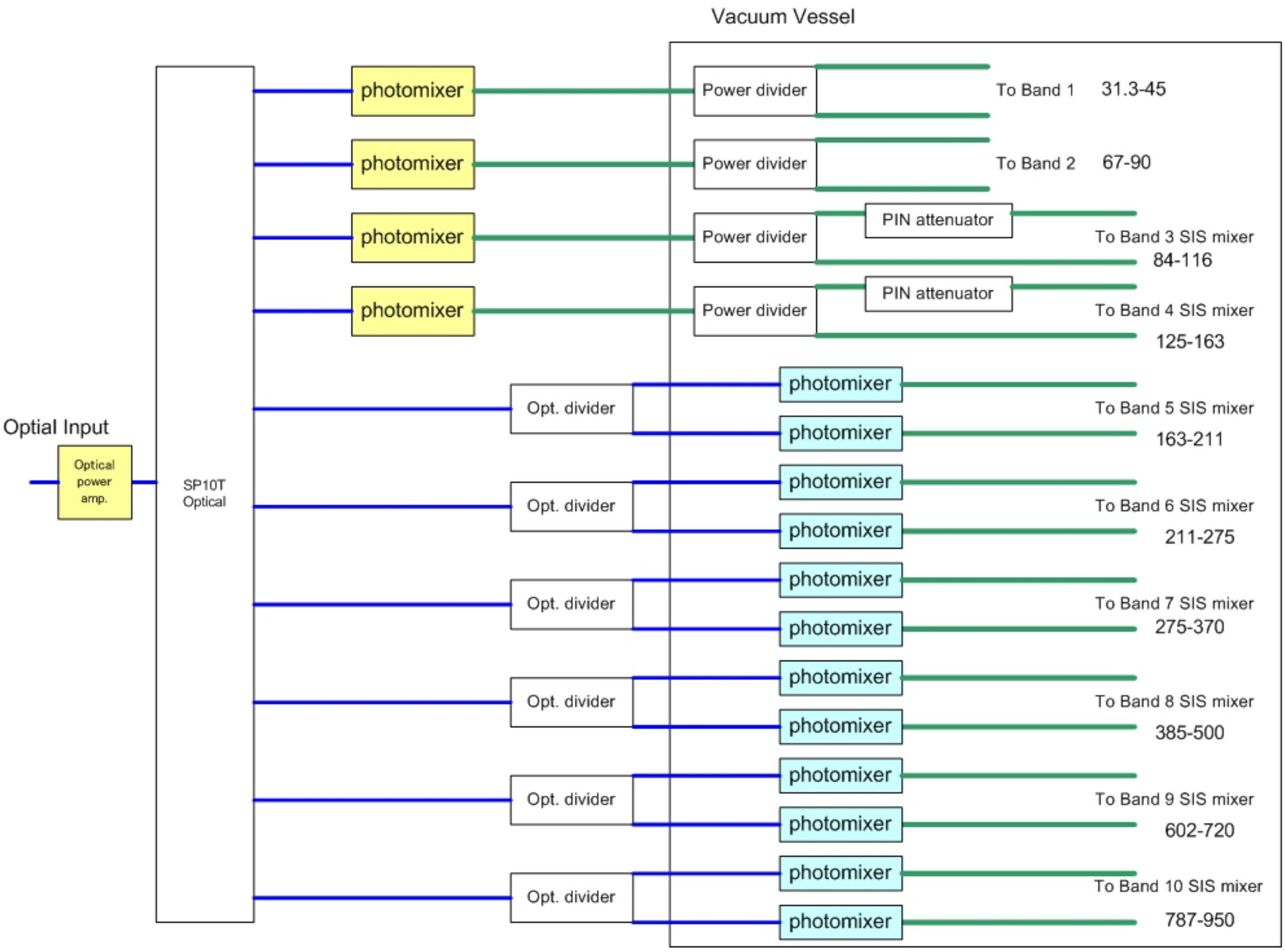
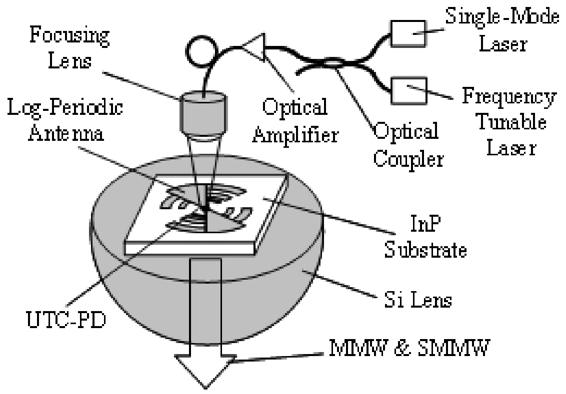


Figure 7: A block diagram for direct photonic LO. The numbers show frequencies in GHz.



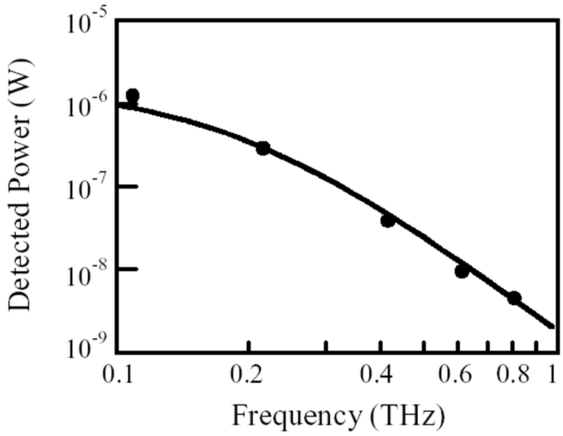


Figure 8: Left: A photonic emitter with a log-periodic antenna. Hirata et al. 2002 [5] Right: A FTS measurement of output power of a photonic emitter with photo current of 0.35 mA.

4.1 Output Power

The UTC-PD is the most promising photodiode to generate signals from microwave to THz frequency range [5, 6, 8]. The W-band photomixer using UTC-PD that achieved the output power of 2 mW at 100 GHz has shown potentialities for direct photonic LO for higher frequencies [3]. Higher output power of 11 dBm at 100 GHz is reported for the UTC photodiodes [15].

In order to evaluate the frequency dependence of the output power over wide frequency range, a free space type photomixer was developed and the performance was measured using Fourier Transform Spectrometer (FTS) for 100 – 800 GHz range [5] as shown in Fig. 8. The measured power decreased approximately proportional to f^{-2} below 200 GHz, and to f^{-4}above 400 GHz (Fig. 8). This tendency can be explained by the CR time constant and the carrier transit time of the photonic emitter. These data extrapolated to photo current of 15 mA (Table 1) indicate that the prospect for direct photonic LO is very high up to band 7 if the photomixer circuit is properly designed. A 350 GHz waveguide photomixer has been developed and a preliminary performance test has started at NAOJ [16].

Table 1: Measured and estimated power of a photonic emitter with a log-periodic antenna. For the UTC-PD, operation with photo current of 15 mA is feasible as shown in Figure 2.

Frequency	Measured Power at $I_{\text{photo}} = 0.35$ mA	Extrapolated to $I_{\text{photo}} = 15$ mA
200 GHz	300 nW	550 μW
400 GHz	40 nW	74 μW
800 GHz	4 nW	7 μW

The laser light power should be the order of 100 mW to generate the maximum power from the UTC-PD with a photocurrent of approximately 20 mA and a bias voltage of -2 V. As the laser power is limited by a fiber nonlinearity (Stimulated Brillouin Scattering) to a few mW, each antenna should be equipped with a low noise optical amplifier. Optical alignment of the fiber launcher to the photodiode chip is very important to get an efficient illumination of the chip. Photodiode chip should be smaller to reduce its capacitance for improving the high frequency response of photomixer. This means that the optical alignment becomes more stringent for high frequency photomixers. There might be a trade-off in the chip size to have a maximum output power at a specific frequency.

4.2 Amplitude Noise

The direct photonic LO driver with a UTC-PD photomixer used for an SIS mixer at 100 GHz demonstrated that the amplitude noise of photonic LO can be reduced to that of Gunn diode oscillator [4]. The signal-to-noise ratio of the combined laser signals with optical amplification and high responsivity of photodiode are crucial to generate a low noise millimeter and submillimeter signals from the photomixer.

Verghese et al. [18] also demonstrated that an SIS mixer at 630 GHz driven with an LTG-GaAs photomixer had comparable noise temperature of around 330 K to that with a Gunn oscillator. In this case, however, a Martin-Pupplett interferometer (MPI) was used as a LO diplexer. Therefore, noise from the LO source can be significantly reduced with the MPI diplexer. The result of Ueda et al. [4] is important because it demonstrated that the low noise photonic LO can been realized with a conventional directional coupler.

4.3 Phase Noise

Phase noise of the photonic LO has not been well understood so far. NAOJ is planning to measure the phase noise of a single photomixer as well as the differential phase between two photomixers driven by the same laser source. In addition, phase stability of the optical amplifier should be studied since it will probably be outside the line length correction loop.

4.4 Cryogenic Operation

As the output power of photomixer is very limited especially at submillimeter wavelengths, it would be better to place the photomixer as close as to SIS mixers in order to minimize the transmission loss between them. This means that the photomixer should be located inside the cryostat. Performance of the UTC-PD at cryogenic temperature is not well understood. It is expected that the optimum light wavelengths could be shifted to shorter wavelengths in proportion to the change in gap energy. A preliminary experiment is being planned at NAOJ to measure the optimum light wavelengths in the course of cooling down by measuring the change in photocurrent. Longer life time is expected when used at lower temperatures. In the case of cryogenic photomixer, only a single optical fiber is needed to feed the LO signal into the front end cryostat. This arrangement simplifies the mechanical interface between the warm part of the cartridge and the cryostat.

If the optical power of 100 mW is delivered to a photomixer, heat load of 200 mW for a band with dual polarization capability is added. For three band of "observing", "next observing" and "calibration" bands, total heat load of 600 mW is added to the cryostat. Then photomixers of direct photonic LO will be installed on either the 15 K stage or 85 K stage.

5 Summary

A W-band photonic LO with UTC-PD has been demonstrated to have high output power and low amplitude noise performance enough to drive SIS mixers. With this photomixer, we have proposed a hybrid option for the first LO in ALMA. This option simplifies LO part of a receiver cartridge. It also facilitates the future extension to the direct photonic LO for all frequency bands. However, the implication to the overall system design such as a phase rotation should be studied carefully. We are preparing another memo regarding laser configuration and their phase lock system which is not included in this memo.

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