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Millimetre Wave Generation Using an Optical Comb Generator with Optical Phase-Locked Loops

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Abstract:
We report the generation of millimetre wave signals to 158GHz with phase noise better than 75dBC/Hz at 100kHz offset, by heterodyning of two lasers which are optically phase locked through an Optical Comb Generator.

Introduction:
The Atacama Large Millimetre Array (ALMA) project [1] is a large-scale international collaboration in Radio Astronomy. A large phased array system consisting of 60 moveable high gain dish antennas will be built in the Atacama dessert in Chile. This radio telescope is designed to operate at frequencies to 950GHz using high frequency mixers and a local oscillator signal is needed to drive these mixers. Optical methods for generating this local oscillator signal are being explored and in this paper we report on a system using a master laser, optical fiber based Optical Comb Generator (OCG) and slave laser, all optically phase locked through two optical phase lock loops (OPLL). The system is capable of generating beat frequency signals with the required noise performance for the full range of the ALMA local oscillator frequency range and has been demonstrated to 158GHz, currently limited by the response of the photodiode used. Other collaborators are developing high-speed photomixers to cover the full frequency range [2,3].

The system reported here is based on heterodyning the output of two 1.55μm lasers on the surface of a wideband photodetector. To produce a low noise beat frequency signal it is necessary for the two lasers to be optically phase locked. To avoid the need for a wideband optical phase lock loop we make use of an OCG. The slave laser is optically phase locked to a line of the comb generator which is itself optically phase locked to the master laser.

Experimental setup:

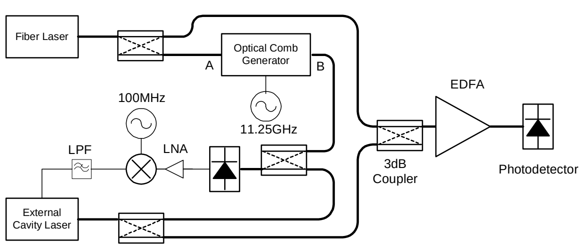

Fig. 1. Complete system. LPF: Low Pass Filter; LNA: Low Noise Amplifier; EDFA: Erbium Doped Fibre Amplifier

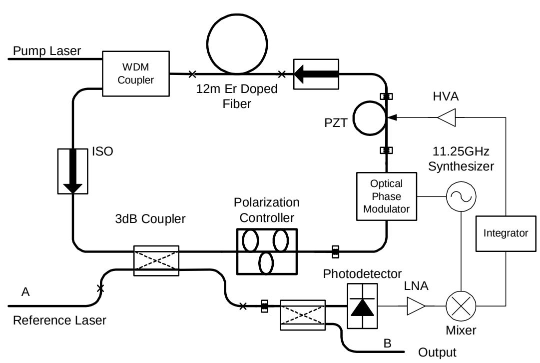

Fig. 2. Optical comb generator with a fibre stretcher to stabilize the comb. HVA: High Voltage Amplifier; ISO: Optical Isolator; PZT: Piezoelectric fibre stretcher

The complete system includes an OCG and an OPLL, as shown in figures 1 and 2. The OCG is a fiber ring laser with a phase modulator (Sumitomo TPM 1.5-40) inside the loop [4,5]. The gain inside the loop is provided by 12m of erbium-doped fiber (EDF) backward pumped by a 1480nm pump laser with a pump power of 40mW. Two isolators are used to ensure that the light propagates only in one direction, and to avoid unwanted reflections. The phase modulator is polarisation dependent and so a polarisation controller is required before the phase modulator. Dispersion compensation and polarisation maintaining components are not used. Input and output for the comb generator is via a 3dB coupler. A stabilized fiber ring laser [6] is used as a master laser to which the OCG is phase locked, resulting in a stable and broadened comb. The output from the OCG is mixed with an external cavity laser (New Focus 6328). A low bandwidth photodiode is then used to detect the beat note signal between the slave laser and the nearest comb line. By comparing the phases of the beat note signal and the 100MHz reference signal, a phase error signal can be recovered and used to modulate the frequency of the slave laser in the usual way, to achieve phase locking of the slave laser to the chosen comb line. By heterodyning the master laser and the slave laser outputs, which now have a frequency difference fixed by the OCG, high frequency signals can be generated without residual mode noise or harmonics from the comb generator.

Results:

When there is no injected signal from the master laser into the OCG, active mode-locking can be achieved inside the loop by driving the phase modulator at a frequency close to an integral multiple of the frequency difference between the cavity modes [7]. The locking range is 50kHz, i.e. the modulation frequency can be tuned by 50kHz while still maintaining mode locking. Dispersion tuning is also observed [8]. The average dispersion slope inside the loop is 11ps/nm/km and this causes a wavelength dependence of the cavity mode frequency difference. This results in an increase in the central frequency of the group of mode-locked cavity modes as the drive frequency is increased. The output is an optical pulse train, with a repetition rate determined by the modulation frequency. In the RF domain, there are many harmonics of the modulation signal. Residual cavity modes can produce unwanted RF beat frequency signals. Furthermore, spurious signals at an offset of 10~20kHz, produced by beating between different mode groups at different wavelengths can greatly degrade the signal to noise ratio. Temperature changes also affect the centre frequency of the comb.

When light from a stable reference laser is injected into the OCG, much more stable operation can be achieved. Of course, it is important that the absolute frequency of the reference laser must be coincident with one of the possible lasing modes of the OCG and the gain in the OCG must also be adjusted to achieve optimum injection locking. Stabilising the reference laser and the OCG separately is not sufficient to produce a stable comb. In our experiment, three different types of laser were used as the master laser. A DFB laser and an external cavity laser were initially used and were found to be insufficiently stable to allow the OCG lock to them. Even with a fibre laser, which has excellent frequency stability and drifts very slowly over a range of around ±10MHz, with a drift rate of 10MHz/min, we were unable to produce a stable comb for more than 10 seconds. Locking the master laser and the OCG together is therefore necessary. We have used an OPLL to do this, either by locking the master laser to an OCG comb line or by locking the OCG to the master laser. In the first case, we used an external cavity laser and exploited the master laser frequency dependency on injection current. In the second case, we used a fibre master laser and inserted a PZT fibre stretcher into the OCG loop (figure 2). By extracting part of the optical signal at the output of the OCG, the detected fundamental frequency was phase compared with the original drive signal and the resulting error signal is integrated to control the fibre stretcher. Using this method, the stability of the OCG was greatly improved.

The fibre stretcher has a limited range, and a mode jump occurs at the end of the range. To maintain stable operation, the fibre stretcher must have a range greater than the thermal expansion of the fibre ring and this is given by $L\eta\Delta T$, where L is the loop length, η is the thermal expansion ratio and ΔT is the maximum temperature drift. The master laser drift is typically less than 20MHz and can be ignored in most cases. In our case the fibre loop length is 30m, η is 30ppm per degree and the fibre stretcher range is 5mm. This allows a temperature change of 0.5°C without mode jumps. During the experiment, we found that stable operation could be maintained for up to 30 minutes. Further improvement can be achieved by using a larger range fibre stretcher, or by including some active temperature control.

The comb shape generated when master laser injection is used is affected by the polarisation state of the master laser, the pump laser power and the master laser power. In general, more pump power results in a wider and flatter comb. The comb width is increased when master laser injection is used but is limited by the dispersion induced unequal mode spacing [9] and the EDF gain bandwidth. In our experiments, we produced a 5nm wide comb in a 10dB envelope as shown in figure 3. The modulation frequency is 11.25GHz and can be tuned continually by more than 200kHz without significant change to the comb shape. The slave laser is locked to one of the comb lines using an OPLL with an offset of 100 MHz. With a flat comb generated by the OCG, locking of the slave laser to a comb line ±258GHz from the master laser (23rd harmonic of the modulation) is readily achieved (figure 4). The output of the slave laser is heterodyned with the master laser as shown in figure 1. Since the signals from the lasers do not pass through the OCG, the flatness of the beat note power generated is determined solely by the photomixer response and the slave laser intensity dependence on wavelength. With an ideal photomixer, flatness of better than 1dB can be achieved within a limited range (4nm, 500GHz). The high-speed photomixer that we used in the experiment is a novel design with output in WR10 waveguide developed by Rutherford Appleton Laboratories and the University of Kent [2] using a photodiode chip from u2t Photonics AG. It is limited to a maximum optical input power of 10mW and has a responsivity of 0.4 with a flat response (5dB) throughout the 75 to 110GHz waveguide band. Outside the band at 158GHz, the response is down by about 18dB. We detected –4dBm at 78GHz and –32dBm at 158GHz (with the external cavity laser as master laser). The signal to noise ratio degrades slightly with increase in harmonic number, but does not follow the usual square law. From the 2nd to the 8th harmonic there is a 0.5dB decrease. The measurement system noise begins to contribute to the total noise at 123GHz, as shown in figure 5. Note that these measurements are taken with different optical power and with different photodetectors and the detected power is not normalised.

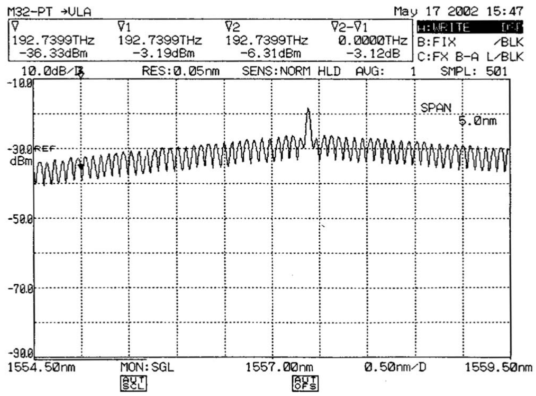

Fig. 3. Optical spectrum of the comb generated at a modulation frequency of 11.25GHz. The peak is the master laser.

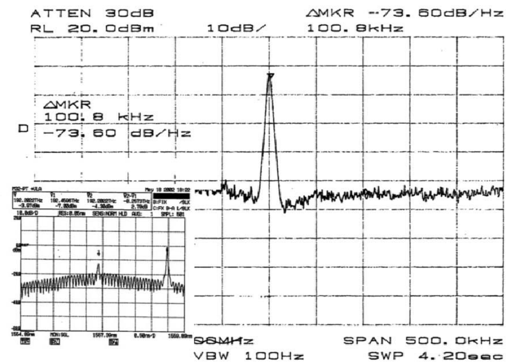

Fig. 4. The slave laser locked to a comb line 258GHz away from the master laser frequency. Picture shows the locked IF signal at 100MHz in the slave laser OPLL. Insert figure: Composite optical spectrum of OCG and slave laser

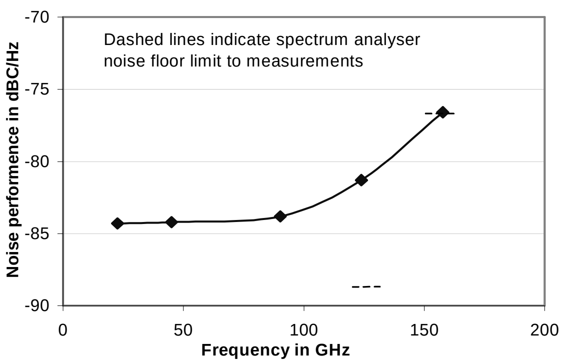

Fig. 5. Measured total noise as a function of the slave laser offset frequency. Measurements are taken at 100kHz offset from the signal

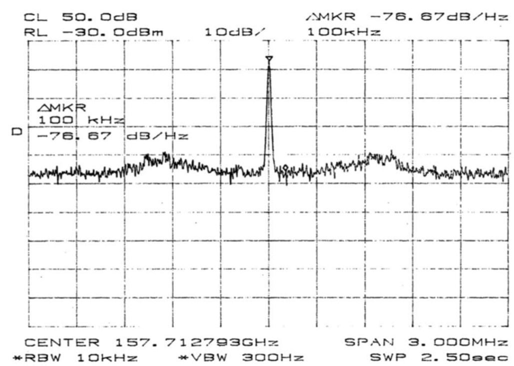

Fig. 6. Typical mmw signal, at 157GHz generated by heterodyned phase locked master and slave laser.

In order to explore the source of the additional noise it is possible to compare the RF signals generated directly from the OCG by heterodyning comb lines, with signals generated by master-slave laser heterodyning. A very clean signal is observed from OCG comb line heterodyning with a noise level better than –100dBC/Hz at 100kHz offset for the 4th harmonic of the modulation frequency (figure 7). In comparison the master-slave laser heterodyne process has a signal-to-noise performance almost 16dB worse. This is a very clear indication that the main noise source is the slave laser, which has a linewidth of 150kHz. The bandwidth of the PLL is limited to a few hundred kHz due to the frequency response of the slave laser's injection tuning, and this is not sufficient for the PLL to track out all of the slave laser's intrinsic noise. Even at an offset from the signal that is smaller than the PLL locking bandwidth, there is still significant additional noise. This noise is also seen when locking the master laser and slave laser though a PLL directly without the use of a comb generator. Using a multi-section laser as a slave laser and reducing the loop length is known to improve the locking bandwidth and to improve the noise performance of an OPLL [10].

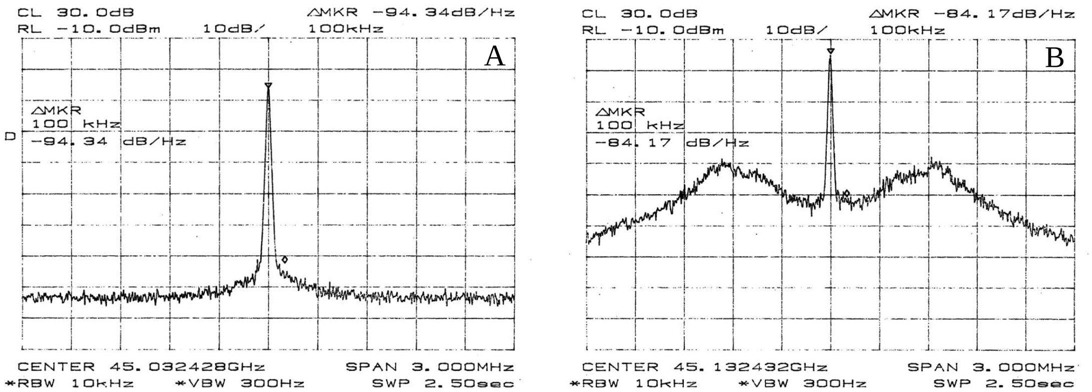

Fig.7. Noise performance. A: 45GHz beat frequency signal from the OCG. B: 45GHz beat frequency signal from master and slave laser heterodyning process

Summary:

We have reported a system for generating millimetre wave signals by optical heterodyning of two lasers that are optically phase locked via an optical comb generator. The system has general applicability wherever a tuneable mmw source is required. In ALMA the LO must be transmitted over many kilometres and optical heterodyning allows the two optical signals from the master and slave laser to be transmitted long distances over fibre without significant degradation. We believe with an improved slave laser OPLL, the signals generated will meet the ALMA phase noise and intensity noise specifications and the frequencies could be fully tuneable over the full ALMA local oscillator range of 30 to 950GHz. We have generated millimeter wave signals to 158GHz by optical heterodyning with phase noise better than 75dBC/Hz at 100kHz offset.

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