Quasi-Optical Stabilisation Of Millimetre Wave Sources

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Abstract - A novel tunable quasi-optical scheme is presented to provide stabilisation of both fundamental and second-harmonic oscillators at W-band (75-110GHz), with excellent isolation from the load. A reduction of phase noise by more than 40dB on free-running Gunn oscillators at 90GHz is demonstrated with SSB phase noise better than -120dBc/Hz at 100kHz away from the carrier. This stabilisation scheme uses external high Q transmission and reaction stabilising cavities, where coupling is achieved using beam-splitters with low power loss. The technique can be directly applied to improve the performance of existing oscillators and is easily applicable at higher and lower frequencies. When used in conjunction with active locking it can provide state of the art performance.

INTRODUCTION

In the millimetre wave band, frequency standards for heterodyne metrology are normally based on phase locking a Gunn oscillator or Klystron to a low frequency standard that has been multiplied up in frequency. The phase noise of the standard is also multiplied up by $20\log_{10}(N)$ where N is the multiplication factor. Short term stability thus degrades significantly as the multiplication number decreases. A state of the art 10MHz source with thermally limited wideband SSB phase noise at the -180dBc/Hz level will be degraded to at least -100dBc/Hz by the time it is multiplied up to 100GHz (without filtering). Conventional techniques for achieving wide-band, high gain phase locking over large offset frequency ranges (up to 1MHz) are also usually complex, expensive, and the best ones are often not significantly tunable.

Local oscillator phase noise in heterodyne systems is important because this noise is also downconverted if any other "large signal" is present. This noise may mask other small signals or introduce uncertainty in the measurement. Even with homodyne systems, standing waves in the system or signal delay may introduce significant FM to AM conversion and increase the effective system noise floor. The phase noise of the local oscillator is often a critical parameter in Doppler radar systems. W-band is also the highest frequency where reliable low noise, tunable, medium power solid state sources are readily available. In long frequency chains, it therefore makes sense to stabilise the local oscillator at this point before multiplying to higher frequencies. One application might be referencing submillimetre wave, infrared or even optical frequencies to national frequency standards in the microwave region.

Frequency noise in solid-state oscillators is usually associated with tiny changes in the effective susceptance of the active device at the rf frequency. Changes in susceptance will be related to temperature fluctuations, rf and bias fluctuations, as well as stochastic effects within the diode which may be strongly dependent on impurities.

One well known solution to improving the short term stability of an oscillator at microwave frequencies is to couple an oscillator to an external high Q cavity. The circuit impedance now seen by the diode means that small changes in the diodes susceptance correspond to smaller frequency deviations, thus reducing the F.M. noise. Cavity stabilisation can be achieved by either linking the cavity to the oscillator as a reflection, transmission or reaction circuit [1]. All three types of stabilisation have advantages and disadvantages in terms of loaded Q, output power, "locking range" and degree of stabilisation at different offset frequencies [1,2]. Critical parameters are the phase distance between the oscillator and the stabilising cavity, the unloaded Q of the stabilising cavity, the coupling parameters to the cavity, and the effective load impedance. For cavity stabilisation schemes in waveguide, this calls for precision circuits which are integral to the oscillator. These have limited Q's, are usually expensive, never wide-band tunable, and difficult to manufacture at W-band.

However, by using a quasi-optical set-up it is possible to make completely tunable cavities with Q's orders of magnitude larger than those obtained in waveguide, thus producing significantly larger stabilisation factors. It is also possible to produce very precise tunable loads, and wide-band quasi-optical isolators with very significant performance advantages over their waveguide equivalents [4]. This means that optimum tuning conditions, low loss, high stabilisation and isolation can be achieved. As an external technique it can also be applied easily to existing local oscillators and is suitable for incorporation into existing quasi-optical systems. This method promises the ideal of being able to place a "noise eating box" in front of almost any local oscillator, to provide near state of the art F.M. noise characteristics, at the cost of only a few dB of output power.

QUASI-OPTICAL STABILISATION

Two schemes that have been implemented are shown in Figures 1 and 2. These both use corrugated feedhorns as mode converters to produce a highly pure Gaussian beam, and then couple to the cavity mode using highly transmissive dielectric beam-splitters or widely spaced polarising grids [6,7]. This novel technique allows excellent spatial matching to the cavity mode, and negligible excitation of higher order modes. It also allows the effective phase length between the oscillator and cavity to be varied, and for the cavity to be tuned without difficulty.

Figure 1 shows a quasi optical version of a reaction cavity followed by a tunable load (optional). A reaction cavity scheme is relatively easy to implement and offers the least power loss for a given loaded Q. It has been shown theoretically that a tunable load can offer further improvements

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in stabilisation, power output and "locking bandwidth" [1]. A rotatable, moveable roof mirror positioned behind a polariser can provide any load impedance with almost negligible insertion loss [3,4]. By moving the roof mirror laterally the phase of the return signal can be changed, whereas rotating the roof mirror alters the amplitude of the return signal. This level of control of the circuit impedance would be difficult to achieve in waveguide at W-band, even with considerable insertion loss.

Figure 2 shows a quasi-optical implementation of a transmission cavity. This is a more complex method as it involves positioning three mirrors, but does added control of the input and output coupling. A transmission cavity has the advantage of filtering out any other spurious signals away from the carrier but has a larger insertion loss. This is due to extra resistive loss that must be placed between the oscillator and the cavity to reduce unwanted resonances.

The degree of stabilisation is directly related to the ratio of the loaded Q's of the single oscillator and the cavity stabilised system. Open cavities are well known to provide very high unloaded Q's and Finesses in excess of 3000 have been demonstrated [6], where the round trip cavity loss is fundamentally limited only by the resistive losses in the end mirrors. A metre long open cavity can have a loaded Q in excess of 1,000,000. This should be compared to a near state of the art waveguide cavity Q of 7,000 at 94GHz and typical Gunn oscillator Q's of 100. Open cavities can provide much larger degrees of stabilisation than previously achieved.

These high loaded Q's can in part be attributed to the beam-splitter coupling, which contributes negligible loss compared to the resistive loss in the end mirrors, and allows excellent spatial matching to the propagating Gaussian beam. This also allows the use of cavities with relatively low Fresnel Numbers (typically unity), which can help to discriminate against higher order modes [8]. In addition, the coupling parameter is now a slowly varying function of frequency which allows the exploitation of wide-band techniques.

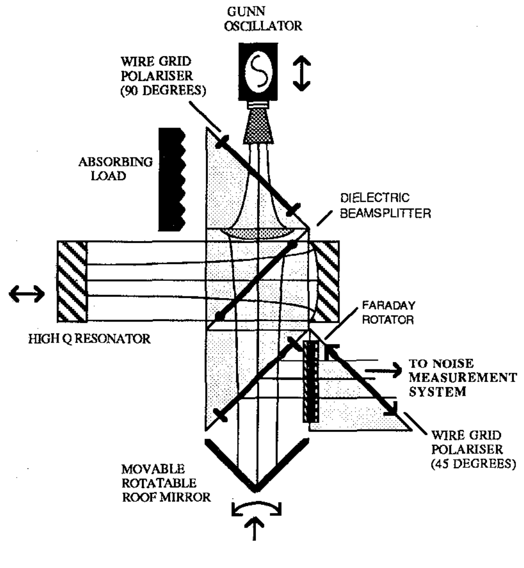

Fig. 1. Schematic diagram illustrating a quasi-optical implementation of a stabilising reaction cavity and tunable load.

This should be contrasted with "small hole coupling" between a waveguide and an open cavity, where the coupling parameter is a very sensitive function of frequency. This type of coupling scheme can also excite higher order cavity modes, and the hole can act as a scattering centre reducing the Q of the cavity.

ISOLATION

Isolation from the load is another important parameter, as any reflected beam will coherently add or subtract from the main field, introducing phase and frequency deviations. However, large quasi-optical Faraday rotators in conjunction with wire-grid polarisers can provide wide-band isolation >30dB, with very low insertion loss <0.5dB, and negligible return loss [5]. These can be used in series, and have also been optimised at higher frequencies and are relatively inexpensive. The ferrite (FERROXDURE 330) is self-magnetised and so does not require an external magnet, which makes it extremely easy to use in many quasi-optical system applications. It is machined to a thickness which gives a 45 degree rotation for a single pass through the ferrite. It has a large refractive index at millimetre wave frequencies and requires matching to reduce multiple reflections which lessens the effective isolation. At the present time, Flourosint is used as a low loss quarter wavelength matching material.

RESULTS

At W-band the phase noise above ~50kHz is now so low that it is not possible to measure the FM noise using conventional down conversion techniques. This is because the harmonic reference used in spectrum analysers at W-band is now very significantly more noisy than the stabilised source at large offset frequencies. The noise was measured using a quasi-optical carrier suppression system developed at St Andrews in conjunction with with NPL Malvern [6], which is shown schematically in Figure 5. It uses an open cavity in reflection to obtain the maximum sensitivity. It is believed this has a lower noise floor than any other equivalent system for the measurement of short term noise at this frequency.

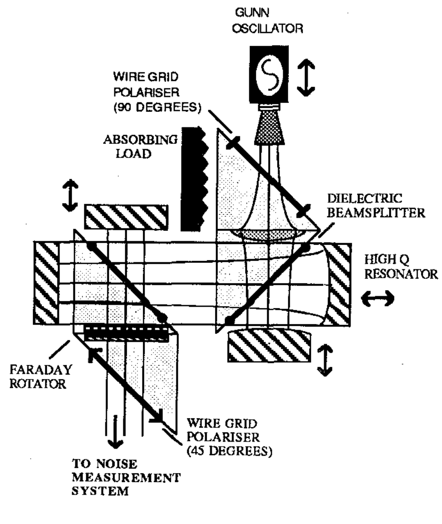

Fig. 2. Schematic diagram illustrating a quasi-optical implementation of a stabilising transmission cavity.

The phase noise of a second-harmonic Gunn oscillator at 90GHz stabilised to a reaction cavity with a loaded Q of 148,000 is shown in Figure 3. The locking range was of the order of 10MHz, and the power loss was less than 3dB. The F.M. noise of the free running oscillator is also shown for comparison. Similar results have been obtained with transmission cavities which offer better stabilisation at offset frequencies very far from the carrier. Figure 4 shows the same oscillator stabilised by a transmission cavity with a loaded Q of 70,000. The system noise floor is also shown.

At 100kHz away from the carrier the SSB phase noise can be better than -120dBc/Hz, which compares to -105dBc/Hz for the best phase locked sources at this frequency. On first inspection this is a surprisingly good performance for second harmonic sources. However, a high Q second harmonic circuit can influence the fundamental frequency of the oscillator through feedback through the diodes non-linearity. The stabilisation of second-harmonic sources is of particular interest because they can provide excellent wideband tunable sources [9]. Smooth tuning with more than 50mW of output power over 15GHz ranges has been achieved at W-band with maximum powers above 80mW. In addition, longer life can be expected from the use of lower fundamental frequency diodes.

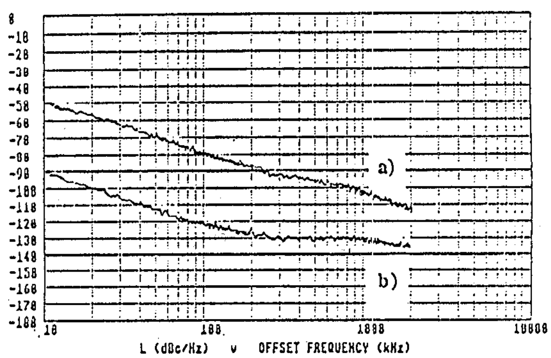

Fig. 3. a) SSB phase noise of a free-running second harmonic Gunn Oscillator operating in second harmonic mode at 90GHz.
b) SSB Phase noise of the same Gunn Oscillator when stabilised by a high Q reaction cavity (Q~148,000).

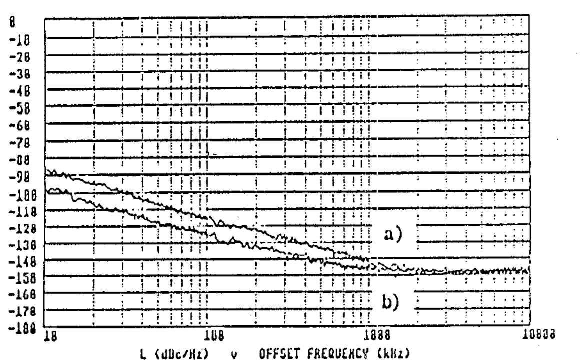

Fig. 4.a) SSB phase noise of a second harmonic Gunn oscillator at 90GHz stabilised by a high Q transmission cavity (Q~70,000)
b) System noise floor for this measurement.

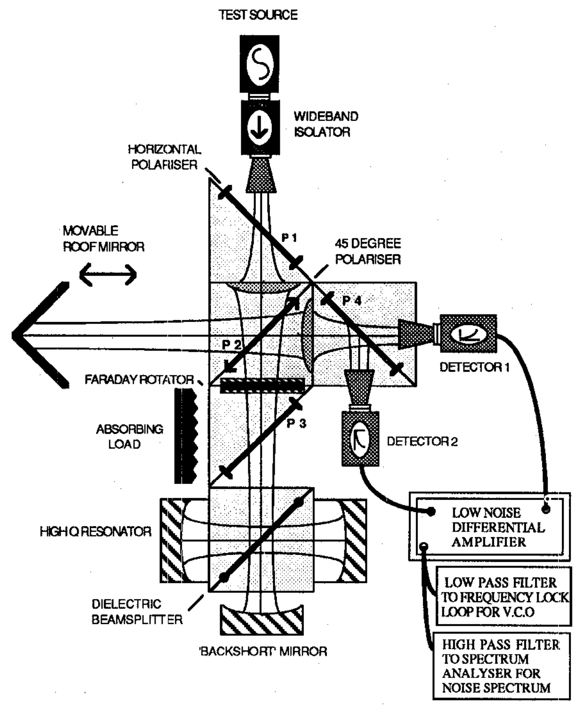

Fig. 5. Schematic diagram of the FM noise measurement system, which can also be used to actively stabilise the source. Polariser P2 splits the signal equally between two paths. The "three mirror" high Q resonator acts as a carrier suppression filter, the Faraday rotator as a circulator, and the movable roof mirror acts as an adjustable phase shifter.

ACTIVE LOCKING

The effect of the high Q resonator coupled to the oscillator is analogous to a frequency lock with a gain which is related to the ratio of the loaded Q of the coupled cavity oscillator and the loaded Q of the original oscillator. However, the long term stability of the stabilised oscillator is still dominated by long term temperature changes within the active device, or small drifts in bias voltage. These, ultimately can make the cavity resonance and the oscillator resonance drift too far apart, and for the oscillator to lose "lock". This situation may be considerably improved by narrow-band phase locking to a harmonic reference, which may also provide an absolute frequency reference. This has been demonstrated in this system by simultaneously locking to an EIP counter, which has a maximum locking bandwidth of 10kHz. This scheme provides readily obtainable ultra-stable sources that can be tuned across W-band, with excellent long term and short term stability.

It is also possible to obtain further improvements in short term noise by actively locking to a very high Q reference cavity, such as that used in the quasi-optical noise measurement system [5]. This is analogous to the active stabilisation technique first described by Pound [10]. The noise floor is now determined relative to the measurement system noise (with a correction close in, related to the Q of the resonator).

In terms of phase noise to carrier ratio $N(\Delta\omega)/C$ (dBc/Hz), the effective noise floors at an offset frequency $\Delta\omega$, for the different stabilisation systems are approximately given by:

Transmission Cavity Stabilisation:

$$N(\Delta\omega)/C \approx N(\Delta\omega)/C_{unstab} \text{ (Noise of unstabilised oscillator)} - 20\log(Q_{L\,stab}/Q_{L\,unstab}) \text{ dBc/Hz} \quad (1)$$

where $Q_{L\,unstab}$ is the loaded Q of the oscillator, and $Q_{L\,stab}$ is the loaded Q of the oscillator while stabilised by the external cavity, and assuming the same resistive loading conditions.

Active locking to a harmonic reference:

$$N(\Delta\omega)/C \approx N(\Delta\omega)/C_{ref} \text{ (Noise of reference source)} + 20\log(N) \text{ dBc/Hz} \quad (2)$$

where N is the harmonic multiplication factor.

Active locking to a matched reference cavity:

$$N(\Delta\omega)/C \approx \text{Effective Measurement Noise Floor (dBc/Hz)} + 10\log((1+(\omega_0/2Q_L\Delta\omega)^2) \text{ dBc/Hz} \quad (3)$$

where the Measurement Noise Floor is measured under operating conditions, Q_L is the loaded Q of the matched reference cavity, ω_0 is the carrier frequency and using the assumption that the reference cavity is perfectly stable.

Typical values for these noise floors at W-band are illustrated schematically in Fig. 6, based on experimental results. A phase lock to a good harmonic reference is likely to give optimum performance for very close in noise. Further from the carrier, locking to a reference cavity may give optimum performance, especially if the power level is high. Ultimately at some frequency a free-running oscillator stabilised by a very high Q transmission cavity will always give optimum performance, and further active stabilisation beyond this bandwidth will only increase the noise level.

It should be noted in both cases, the implementation of active locking is made considerably easier when used in conjunction with cavity stabilisation. This is because the amount of gain and bandwidth required of the loop has been very significantly reduced. This is of particular relevance in situations where upconverted noise from the control voltage limits the gain in VCO's. This is true in situations where the source tuning constant is very large such as Flux Flow Oscillators and many types of Travelling Wave Tubes.

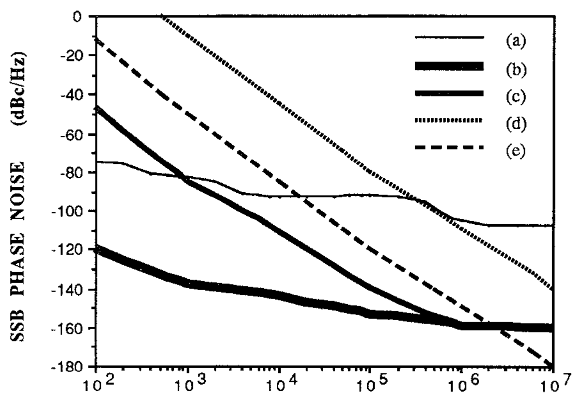

Fig. 6. Graph illustrating typical SSB phase noise measurements, and phase noise floors for each type of stabilising system at 90 GHz.

a) Phase noise of a good multiplied source
b) Typical effective measurement system noise floor
c) Noise floor for active cavity stabilisation (Q_L =100,000)
d) Typical phase noise of a free-running Gunn oscillator
e) Phase noise after cavity stabilisation (experimental result)

CONCLUSIONS

The combination of a narrow band phase lock to optimise and a high Q stabilising cavity can provide exceptionally stable oscillators at W-band. This Quasi-Optical stabilising system allows almost complete control of the circuit impedance seen by the diode and allows the use of extremely high Q cavities. This technique is applicable to almost any existing oscillator at W-band or above, at any frequency. It has been shown to work well with second harmonic Gunn sources opening up the possibility of having very wide-band tunable ultra-stable sources. The technique has direct applications in providing improved performance tunable sources for frequency chains and precision heterodyne metrology. It also has applications in improving the spectral quality of some high power sources where upconverted noise from the power supply is the main contributor to FM noise levels. It offers very significant improvements in performance and promises to be a much cheaper and simpler alternative to high gain wideband phase and/or frequency locking.

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