A HIGHLY SENSITIVE MILLIMETRE WAVE QUASI-OPTICAL F.M. NOISE MEASUREMENT SYSTEM

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ABSTRACT

A highly sensitive, tuneable, low loss quasi-optical millimetre wave F.M. noise measurement system has been constructed, with state of the art performance. It utilises a novel matched, easily tuneable quasi-optical cavity in reflection, to act as a carrier suppression filter. This can operate with matched cavity Q's of several hundred thousand with almost zero insertion loss to provide an extremely high discriminator slope at low power levels. The F.M. noise measurement system can allow direct measurement of phase locked sources at low input power levels over ultra-wideband frequency ranges.

INTRODUCTION

There are essentially two approaches to F.M. noise measurements at high frequencies. The first technique is to phase lock another low noise source in quadrature to the source to be tested. This introduces full F.M. to A.M. conversion, but adds the noise of the additional source. The low noise source is commonly a harmonic frequency of a very stable reference source. However, at high millimetre wave frequencies the phase noise of these systems can start to be significant, as phase noise is also multiplied up with harmonic multiplication. The requirement to maintain phase lock of the two signals in quadrature also becomes more difficult at high frequencies. The other methods are single oscillator techniques, where the carrier is used as the local oscillator and is phase shifted relative to the noise sidebands, using a frequency discriminator. These either involve directly using the slope of a high Q cavity either in reflection (1) or transmission (2), or a delay line (interferometer) (3)(4), or using a carrier suppression technique (Ondria phase bridge method)(5)(6).

Not many W-band phase noise measurement systems using these techniques have been described in the literature. However, Simmons (3) has built a delay line system in waveguide at 80GHz with an equivalent Q of around 1500, and Ondria (6) has described a carrier suppression system at 94GHz using a waveguide cavity with a Q of 6500. Harth (2) has built a direct detection system which used the slope of a quasi-optical cavity with a Q of 30000. However, this was also used in transmission, which meant the system had an additional 17dB of insertion loss.

Noise measurements become more difficult at W-band, because of the lack of suitable amplifiers at the rf frequency, and because waveguide and system losses either reduce sensitivity, or require an increase in the amount of input power required to run F.M. noise measurement systems. Waveguide cavities have Q's which are severely limited by resistive losses, and often are not easily tuneable. These problems become even more severe at frequencies above W-band.

One low loss wideband solution is to perform most of the rf signal processing using quasi-optics (7). Corrugated scalar horns are used to produce highly pure fundamental gaussian beams which can be manipulated using lenses, mirrors and polarisers.

To achieve the highest sensitivity with F.M. noise measurements, a key requirement is to have a low loss frequency discriminator with as large a discriminator slope as possible. The measurement technique used in this system employs a very high Q quasi-optical cavity in reflection to provide an extremely high discriminator slope. Typical values for the matched cavity Q are well in excess of 100,000 with almost zero insertion loss. This is over an order of magnitude better than that previously achieved with waveguide cavities. (An increase in Q by a factor of 10 can be expected to decrease the noise floor by a factor of 20dB).The discriminator slope can be in excess of 1μV/Hz for an input power of a few mW. Compared to delay line techniques at this frequency, the improvement in sensitivity can be better than 40dB. This technique allows very high sensitivity at low input powers over an ultra wideband frequency range.

PRINCIPLE OF OPERATION

The system can be thought of as an optical analogue of the carrier suppression noise system used in waveguide (5) but uses a number of novel quasi-optical techniques to effect extremely high performance. Essentially, the signal is split into two, and the carrier is suppressed in one arm using a high Q reaction cavity, and then reintroduced into the system shifted by 90 degrees. The cavity itself introduces a frequency dependent phase shift and attenuation across the width of the resonance which has the effect of partial F.M. to A.M. conversion. Outside the cavity resonance full F.M. to A.M. conversion is achieved. Balanced mixers are used to distinguish the contributions from F.M. and A.M. noise, and to measure the system noise under operating conditions (5).

Figure 1 shows a schematic of the quasi-optical circuit used in the F.M. noise measurement system at W-band. The oscillator power passes through a wideband waveguide isolator and is then split equally between two arms using polariser P2. The reflected beam acts as the phase reference or local oscillator arm. The phase of this beam can be adjusted

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by changing the position of the roof mirror (which flips the polarisation through 90 degrees), so that it is in quadrature with the signal returning from the resonator arm. The transmitted beam passes through a 45 degree Faraday rotator (which acts as a quasi-optical circulator) towards the "three mirror resonator". The effective isolation produced by the Faraday rotator in conjunction with the polarisers is greater than 30dB across most of W-band, with a VSWR between 1.1-1.4 and an insertion loss of 0.3-0.5dB (8). The isolation between the cavity and the oscillator is believed to be greater than 60dB which should prevent self injection locking from the high Q cavity.

The resonator consists of a near confocal cavity which is coupled into via a thin polythene beamsplitter, which is at 45 degrees to the beam and has a power reflectivity of a fraction of a percent. Off resonance, most of the power passes through the beamsplitter and is reflected off the "backshort mirror", and back towards the detection system with almost zero insertion loss. On resonance, power builds up in the cavity, and there is a return signal from the cavity and the "backshort mirror". By altering the phase of the return signal from the "backshort mirror" it is possible to have these two fields cancel at one particular frequency. At this frequency all the input power is absorbed in the cavity, and the cavity is thus fully matched. As the absorption losses in the cavity are small the Q of the cavity can be very large.

Because near resonance, the phase and amplitude of the reflected signal is strongly frequency dependent, when it combines with the reference signal, the polarisation state of the beam emerging from P2 changes rapidly with frequency. This change in polarisation state can be detected by splitting the beam equally, with a horizontal/vertical polariser P4 and detecting the orthogonal plane polarised using two nominally identical mixers.

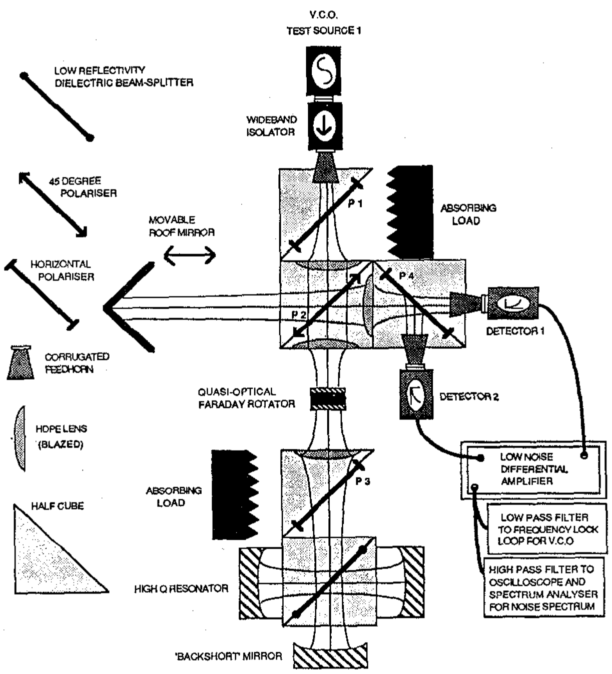

FIGURE 1

Schematic Diagram of the F.M. Noise Measurement System

The detectors are both in custom-built tuneable cavities which allow excellent matching across W-band. In conjunction with the polariser, the two detectors operate as a quasi-optical analogue of a balanced mixer in a hybrid T. The difference signal is amplified using a low noise if amplifier and measures the F.M. noise component and discriminates against the A.M. noise. With careful matching it is usually possible to obtain about 30dB of A.M. rejection across W-band.

Because the resonance width of the cavity can be as low as a few hundred kHz, the oscillator frequency can drift off line centre during the course of the measurement. It is therefore usually necessary to frequency lock the oscillator to the resonator or to lock the resonator to the oscillator. The d.c and low frequency components are used for locking and the high frequency noise is measured on a spectrum analyser and recorded on a computer.

Inside the resonator bandwidth the system acts as a frequency discriminator where any small frequency fluctuation Δf produces a voltage fluctuation ΔV given by:

$$\Delta V = V_B \frac{2Q}{f_0} \Delta f \qquad (1)$$

where V_B is the height of the discriminator curve. Thus for a single sideband measurement the noise to carrier ratio is given by:

$$L(f) = \frac{1}{2} \left(\frac{f_0}{2Qf}\right)^2 \left(\frac{\Delta V_{rms}(1Hz)}{V_B}\right)^2 \qquad (2)$$

where $\Delta V^2_{rms}(1Hz)$ is the noise power measured in a 1Hz bandwidth.

Outside the resonator bandwidth, the noise from the resonator arm is in complete phase quadrature with the signal from the reference arm of the resonator. The system therefore measures $\Delta\phi^2_{rms}$ with a phase detector constant V_B.

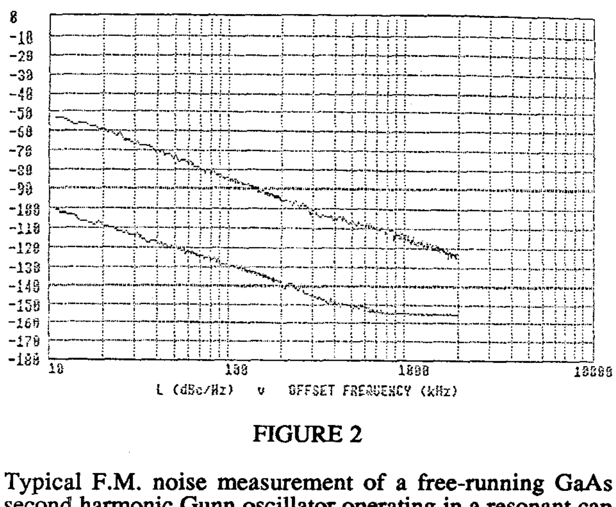

FIGURE 2

Typical F.M. noise measurement of a free-running GaAs second harmonic Gunn oscillator operating in a resonant cap cavity at 88GHz. The system noise floor for thsi measurement is also indicated.

Therefore, any small phase fluctuation $\Delta\phi$ produces a voltage fluctuation ΔV given by:

$$\Delta V(f) = V_B \Delta\phi(f) \quad \text{for } f \gg f_0/2Q \qquad (3)$$

$$L(f) = \frac{1}{2} \left(\frac{\Delta V_{rms}(1Hz)}{V_B}\right)^2 \qquad (4)$$

These correction terms (or alternative calibration data) are then applied and the noise spectrum is printed out. The system noise can be measured by effectively removing the resonant cavity from the system. A typical noise measurement is shown in Figure 2.

CONSTRUCTION OF SYSTEM

The system has beem constructed using a 'half-cube' optical breadboard. The half-cubes have a side-length of 120mm and aperture diameters of 88mm. High density polyethylene (HDPE) aspherical lenses were used to couple the radiation through the system, and to provide spatial matching to the resonant cavity. These lenses also had quarter wavelength blazing to provide low reflection losses in the 90 GHz region. The polarisers were constructed from 25μm tungsten wire at 50μm spacing wound on a flat metal frame using a coil winder. At W-band, the cross-polarisation is typically better than 35dB and the insertion loss is negligible. A photograph of a version of the system is shown in Figure 3.

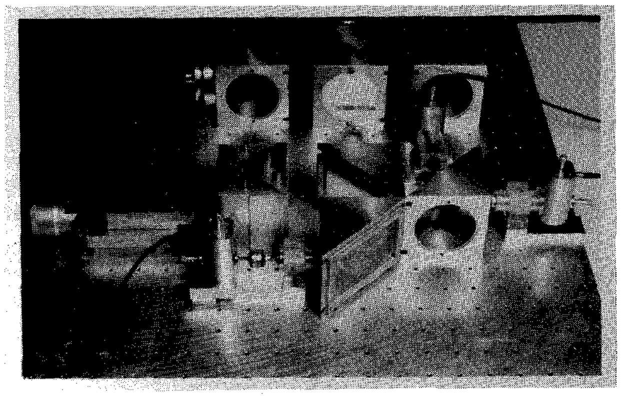

FIGURE 3

Illustration showing construction of F.M. noise system using half-cubes on an optical breadboard.

THREE MIRROR RESONATOR

Coupling to an open resonator with a beam-splitter has been described before by French et al. (10) for absorption measurements, and Goldsmith (11) for use as a single side band filter. Both systems used the resonator in transmission rather than in reflection. This technique has the advantage over small hole coupling in that the coupling is relatively constant over a large frequency range, and that the resonator mode can be spatially matched to the propagating gaussian beam mode. It is also relatively simple to change the beamsplitter within the resonator to provide different coupling at different frequencies.

The "three mirror resonator" is an analogue of many waveguide systems, where full matching to a low impedance device is often achieved by using a series resonance across the waveguide in conjunction with a backshort. We can think of the resonator as an infinite number of simple tank circuits all coupled to the transmission line (free space) via the dielectric beam-splitter. Each of these can be represented as a simple LCR circuit , which is only appreciably excited near resonance. On resonance the load is purely resistive and for small coupling and losses the effective resistance across the transmission line is approximated by:

$$R_{eff} \approx Z_0 \cdot \frac{\alpha_{resonator}}{R_{dielectric}} = \frac{Z_0}{K} \qquad (5)$$

where Z_0 is the impedance of free space, α is the fractional one way power loss, R is the fractional power reflectivity of the dielectric beam-splitter and K is the coupling parameter.

The technique is effectively matching the impedance of free-space to the very small losses in the cavity, and full matching can always be achieved as long as the effective resistance is greater than the impedance of free space. In other words, the power reflectivity of the beamsplitter must be greater than the effective one way power loss in the cavity. (However, the reflectivity of the beamsplitter cannot be too large in comparison though, otherwise significant distortion of the sidebands can occur). For optimum operation, the reflectivity equals the one way power loss.

The power loss in the cavity is made up of absorption losses in the dielectric, absorption losses in the air, diffraction losses, and resistive losses in the end mirrors. Experimental values for the fractional loss α have been found to be approximately 0.1% for copper mirrors and 0.13% for aluminium mirrors. At W-band the losses in the air and dielectric are very small and the diffraction losses can be made negligible with proper design of the resonator cavity (12). In practice, the resistive losses in the end mirrors are thought to dominate. For a mirror of conductivity σ at frequency f the fractional power loss is given by (9) :

$$\alpha_{refl} = 2\,(4\pi\varepsilon_0 f / \sigma)^{1/2} \qquad (6)$$

For copper and aluminium mirrors this leads to respective theoretical absorption losses of around 0.08% and 0.11% for the reflection off one mirror at 94GHz, indicating that the main resistive loss is due to the mirrors.

The figure of merit for a cavity is the finesse which for small loss and beamsplitter reflectivity is given by:

$$\mathcal{F} = \frac{\pi}{\alpha + R} \qquad (7)$$

where α is the one way fractional power loss (or round trip amplitude loss) and R is the reflectivity of the beamsplitter. The maximum finesse is in the limit of vanishingly small R (unloaded cavity). In practice to achieve the maximum discriminator slope the reflectivity of the beamsplitter R is chosen to approximate α, to allow full matching to the cavity, leading to a typical operating finesse of around 1500.

The Q of the cavity is given by:

$$Q = \mathcal{F}\frac{2L}{\lambda} \quad (8)$$

where L is the length of the cavity. The length of the cavity is eventually limited by diffraction losses (12) caused by the finite size of the mirrors, providing a limit to the Q available. Thus for a cavity length of 360mm it is possible to achieve matched Q's in excess of 300,000.

The reflectivity of the beamsplitter depends on its thickness, refractive index and the polarisation state of the incoming beam. In practice, a polythene sheet of approximate thickness 10μm has been used successfully as a beamsplitter. The polaristion state can be flipped simply by turning the circulator around and rotating the polariser P3 through 90 degrees.

PERFORMANCE OF F.M. SYSTEM

The system has been used routinely to measure the free-running F.M. noise characteristics of many different types of diode at W-band under different cavity and bias conditions. It has been tested at different levels of signal attenuation and cavity Q and has shown excellent repeatability and consistency.

The sensitivity of the system as it stands allows F.M. noise measurements of typical free-running Gunn oscillators at W-band at the 50μW power level. 0.5mW is usually sufficient to make measurements on phase locked oscillators at W-band. Measurements have also been performed at 140GHz at power levels of only several hundred micro watts. In association with Nottingham University, it is hoped to be able to make the first F.M. noise measurements on Quantum Well Oscillators operating at W-band in the very near future.

It is also hoped to incorporate a matched pair of indium antimonide detectors into the detection system to further reduce the flicker noise associated with the detectors and substantially further increase the sensitivity, and allow measurements at higher millimetre wave and sub-millimetre wave frequencies.

CONCLUSIONS

To our knowledge, the full use of quasi-optics for this type of measurement system is completely new, as is the matching technique applied to the detectors. In addition, we believe this use of the three mirror resonator system is novel, and overcomes many of the problems associated with small hole coupling into open resonators. In conjunction with the quasi-optical circulator we believe that it represents an advance in state of the art performance, and has many other potential uses such as the measurement of loss and permittivity in dielectrics, sideband filters, scanning interferometry at high millimetre wave frequencies and cavity injection locking of oscillators. Some of the above applications have also been successfully applied at St Andrews.

As a F.M. noise measurement system we believe that in terms of the combination of very wide tuneability, low loss, and high sensitivity it represents an advance in state of the art performance at high millimetre wave frequencies, at a comparatively low cost.

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