Phase-Locked-Loop Control of Active Microstrip Patch Antennas

John W. Andrews and Peter S. Hall, *Fellow, IEEE*

***Abstract*—Active patch antennas are simple to fabricate, compact, and low cost, but have inherently poor phase noise and stability. In this paper, a phase-locked loop (PLL) integrated with a 4-GHz active patch antenna was investigated in order to reduce the phase noise and stabilize the frequency of the oscillator. Both these aims were realized by careful integration and optimization of the PLL parameters. Experimental results showed that a phase noise reduction in excess of 55 dB was achieved using this technique. A standalone voltage-controlled oscillator and passive patch technique can provide lower phase noise, but the active patch lends itself to effective integration. Measurement techniques were demonstrated to measure the phase noise and stability of the patch oscillator.**

***Index Terms*—Active antennas, antennas, phase-locked loops.**

I. Introduction

OSCILLATOR phase noise is a critical parameter in the design of communication systems. For example, Doppler radars determine the velocity of a target by calculating the small shifts in frequency that the return echoes have undergone. Poor phase noise and oscillator stability in either the transmitter or the receiver can mask the target signal [1]. Angle modulated communication systems are another example where phase noise can be deleterious, especially at high data rates.

Techniques such as injection locking, tuned cavity [2], and dielectric resonators are commonly used to stabilize oscillators and to reduce their phase noise. In this paper, a phase-locked loop (PLL) solution is implemented. As well as achieving the prime objectives, the technique also facilitates other enhancements such as carrier frequency control, channel switching, and loop modulation. The technique can also accommodate electronic beam steering for patch antenna arrays by the introduction of an offset voltage at the phase detector output [3]. Phase noise in active integrated antennas is important, and will determine whether or not they are used in future systems [4].

II. Active Patch Antenna

The active patch end-fed rectangular antenna is shown in Fig. 1. It was designed on the Hewlett-Packard Microwave Design System (MDS) and was previously reported in [5]. The active device on the patch oscillator is an ATF-26884 MESFET. The oscillator frequency is controlled by the gate–source MESFET voltage. The resulting voltage-controlled oscillator (VCO) has a sensitivity $(K_{\text{vco}}) \approx 30$ MHz/V.

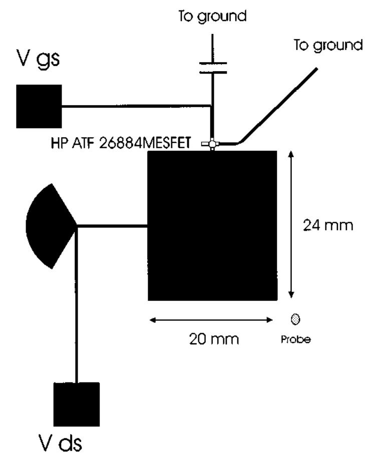

Fig. 1. End-fed rectangular patch antenna.

III. PLL

The PLL chosen was a National Semiconductor LMX2325 microwave frequency synthesizer integrated circuit operating from a 5-V supply up to a maximum frequency of 2.5 GHz [6]. The linear phase detector generates very stable low-noise output signals for VCO control, via a low-leakage charge pump and an external-loop bandwidth filter. The synthesizer characteristics are summarized below:

phase detector type	linear charge pump
RF frequency	up to 2.5 GHz
power requirements	2.7–5.5-V low current
fabrication	AbiC IV BiCMOS
phase detector sensitivity	5 mA/rad
normal environment	mobile communications.

IV. Patch Antenna and PLL Integration and Operation

Fig. 2 shows a schematic drawing of the PLL and associated peripheral blocks. A parallel interface to the PLL via a personal computer (PC) allows the LMX2325 parameters such as divide N and reference frequency to be altered for optimum phase-noise reduction. The loop filter design also plays a crucial role in phase-noise reduction. A sample of the patch output is taken from the patch edge via a coaxial probe coupler to the input of a prescaler (Hewlett-Packard IFD53010). The purpose of the prescaler is to bring the patch frequency within range of the synthesizer frequency response. Dividers within the synthesizer further divide the input frequency by a factor of N; the divided N output provides one input to the phase detector. The

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The authors are with the Communications Engineering Group, School of Electronics and Electrical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, U.K. (e-mail:p.s.hall@bham.ac.uk).

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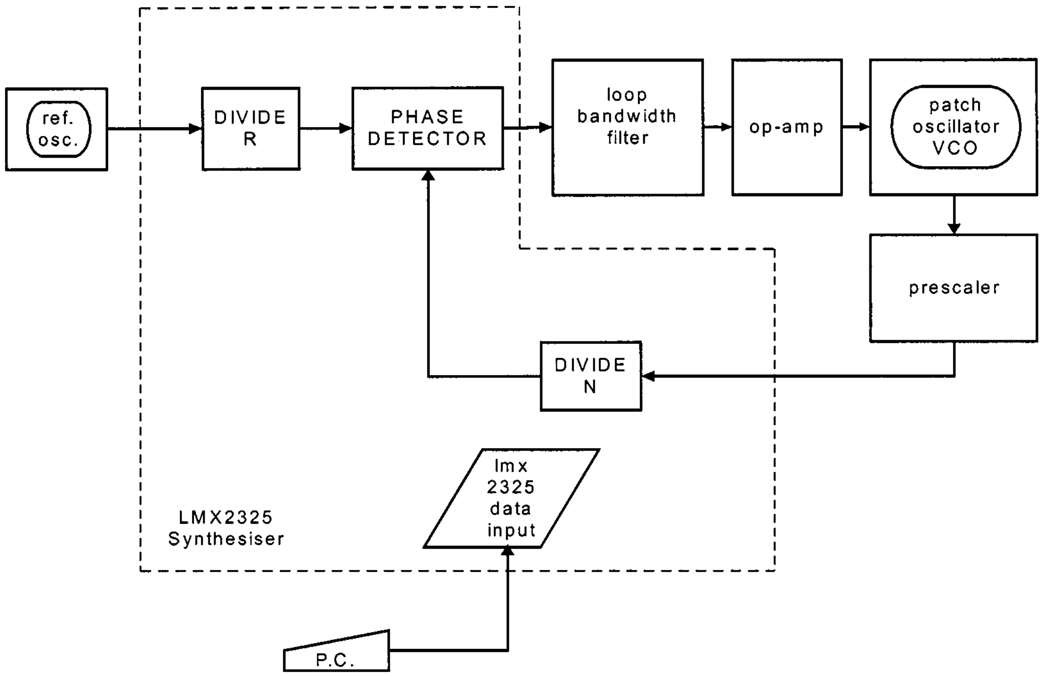


Fig. 2. Block schematic of synthesizer and peripherals.

other phase detector input is sourced from a stable reference oscillator operating at 10 MHz, followed by a frequency division of R. Reference oscillator stability and phase noise is imposed upon the patch antenna oscillator within the loop bandwidth in accordance with standard PLL theory [7]. The phase detector output is integrated via the loop filter and the resulting output fed via an operational amplifier to provide a control voltage to the patch FET gate source. The operational amplifier is necessary to provide both the correct polarity and very low impedance required to drive the patch oscillator FET gate source, albeit it is a further noise contributor.

V. Experimental Procedure

The experimental setup is shown in Fig. 3. The active patch antenna and the PLL are powered from a 5-V power supply (Hewlett-Packard E3631A). A wide-bandwidth antenna placed 30 cm from the patch antenna is used to capture the patch oscillator radiated signal; the signal is then displayed on a spectrum analyzer (Hewlett-Packard 8563E). The spectrum analyzer is connected to a PC via an IEEE-488 interface in order to allow automatic data collection for phase noise and spectrum plots.

VI. Phase-Noise Measurement

The patch antenna has an inherently poor phase noise and stability characteristic. An appropriate measuring method for these characteristics is a delay-line discriminator method (Hewlett-Packard E5501B). Increasing the measurement dynamic range is achieved by eliminating the carrier of the source to be measured [8], leaving only the noise sidebands. The resulting mixer baseband output provides maximum phase sensitivity and linearity. Measurements are performed on the baseband signal via a spectrum analyzer.

The Hewlett-Packard spectrum analyzer (8635E) has a built-in phase-noise facility, where the measurements are at radio frequency. However, measurements by this method are limited by the inherent noise present in the spectrum analyzer local oscillator.

VII. Experimental Results

A. Phase Noise

The 4-GHz patch-antenna phase-noise results using the Hewlett-Packard E5501B delay-line discriminator phase-noise test equipment are shown in Fig. 4. Due to the high level of free-running phase noise, the measurements are in terms of relative levels in units of decibels/hertz. An improvement in the phase-locked phase noise compared to the free-running phase noise is ≈55 dB. As a comparison, using the spectrum analyzer built-in facility, the PLL method gave an improvement of only 26 dB in terms of absolute units of dBcarrier/hertz, as was previously reported in [9]. The reason for the wide discrepancy between the two measurement methods is that the spectrum analyzer method assumes that, at certain frequencies and at certain times, the frequency is phase-locked for a short period and then swept to the next lock point [10]. Due to the patch antenna's inherently poor phase noise and stability behavior, the time window in a measurement period drifts into unrelated windows, especially for the free-running oscillator case. Another limitation of the spectrum analyzer method is the inability to reach close into the carrier, this region being where the largest improvement in phase noise occurs with the PLL technique. The large differences in the measured results emphasize the importance of using an appropriate measurement method.

Units of decibels/hertz are represented by the symbol $S_\phi(f)$, being the spectral double-sideband density of phase fluctua-

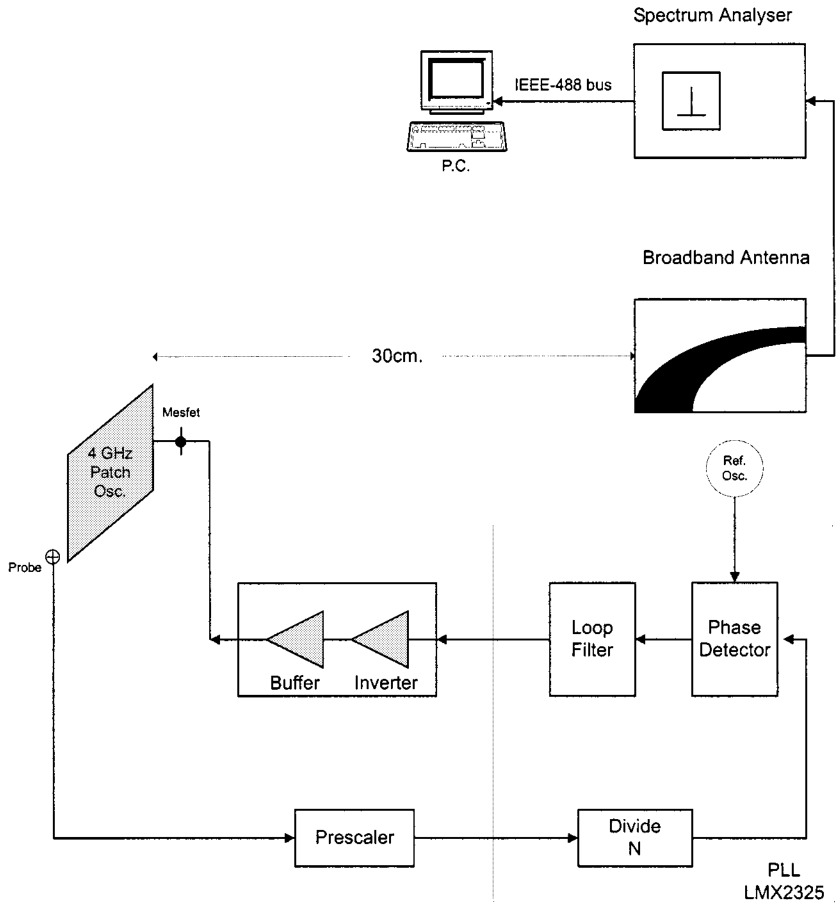


Fig. 3. Block schematic of test setup.

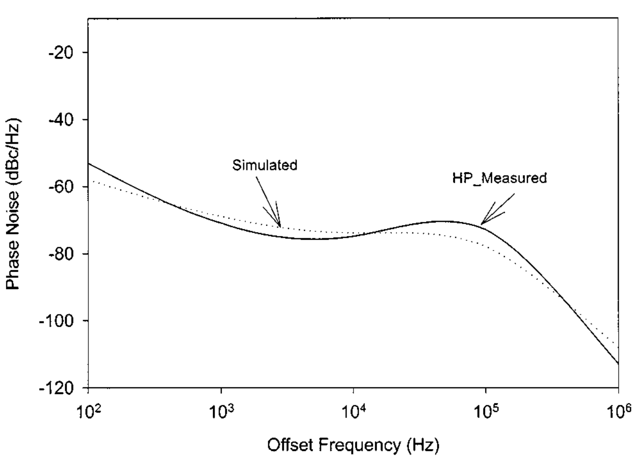


Fig. 4. Measured relative phase noise $S_{\phi}(f)$ (region of validity allows conversion from S_{ϕ} (decibels/hertz) to L (dBcarrier/hertz)—see text).

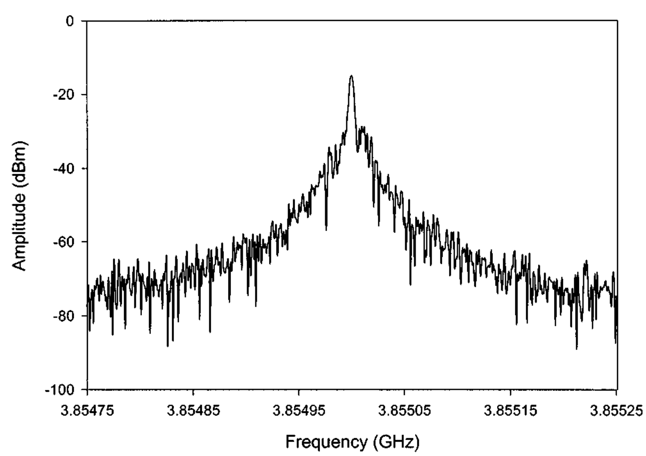


Fig. 5. Locked patch oscillator spectrum (span $= 500$ kHz, $\mathrm{RBW} = 3$ kHz).

tions. Units of dBcarrier/hertz are represented by the symbol $L(f)$, and described as the single-sideband phase noise relative to the carrier signal power. The two symbols are related by the expression

$$L(f) = \frac{S_{\phi}(f)}{2}. \tag{1}$$

$L(f)$ can be directly related to $S_{\phi}(f)$ using phase-modulation theory within the confines of the small angle criterion by allowing for the 3-dB difference between the levels, but is only valid for levels below the “region of validity” [1]. This region is inserted by the phase-noise measurement system. The 3-dB difference further enhances the measured $S_{\phi}(f)$ levels using the discriminator method over the $L(f)$ levels from the spectrum analyzer measurements. The hump in the phase-locked response of Fig. 4 is attributed to the synthesizer and the 100-kHz loop filter response.

Close-in phase noise can be further enhanced by the use of an improved reference source. Also, spectrum-analyzer

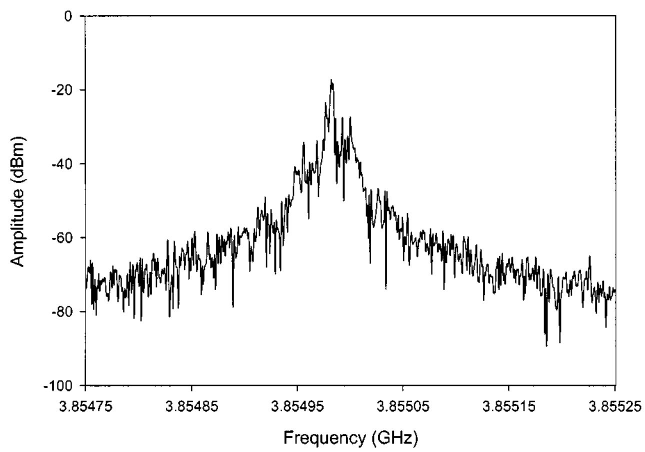


Fig. 6. Unlocked patch oscillator spectrum (span $=$ 500 kHz, $\mathrm{RBW} = 3$ kHz).

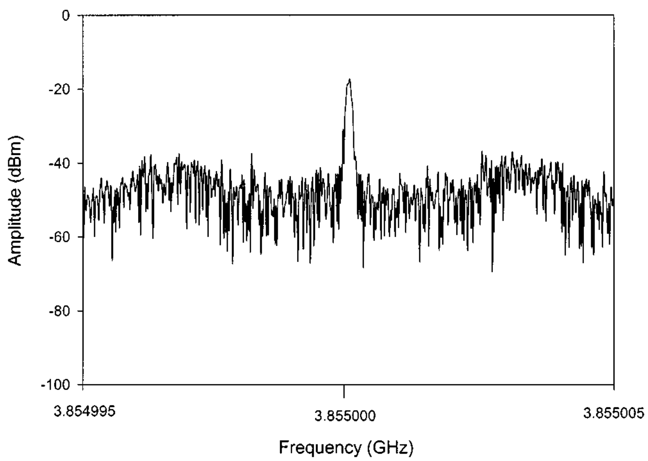


Fig. 7. Locked patch oscillator spectrum (span $= 10$ kHz, $\mathrm{RBW} = 100$ Hz).

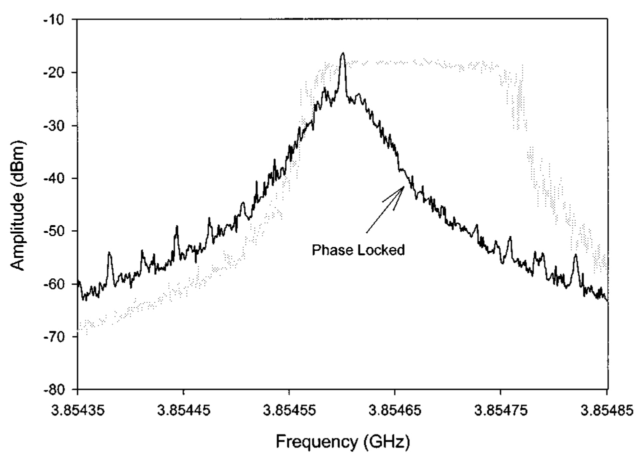


Fig. 8. Stability plot over 60-s period.

phase-noise measurement showed a 10-dB improvement by employing varactor FET gate control instead of direct voltage gate control.

B. Spectrum

Figs. 5 and 6 show the signal spectrums for the PLL locked and unlocked conditions, respectively; they represent a span $= 500$ kHz and resolution bandwidth $(\mathrm{RBW}) = 3$ kHz. Fig. 7 shows that the patch is still stable at a span $=$ 10 kHz and $\mathrm{RBW} = 100$ Hz. The unlocked patch shows no spectral peak at these settings.

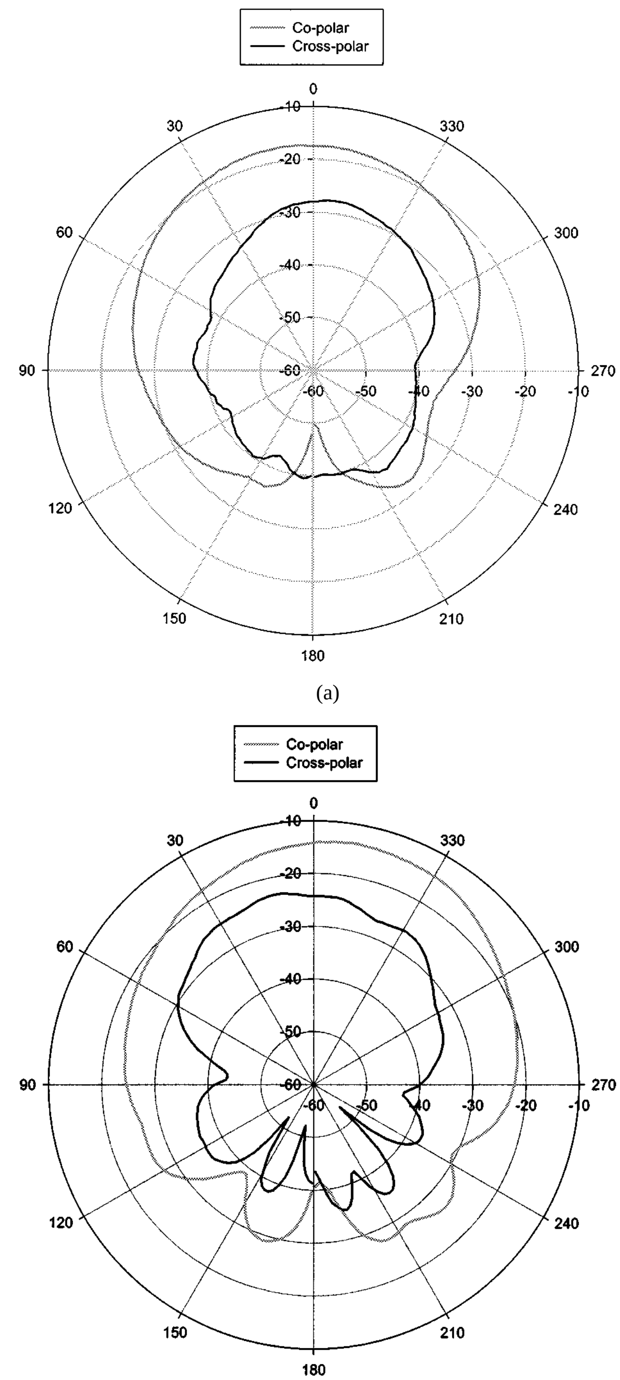
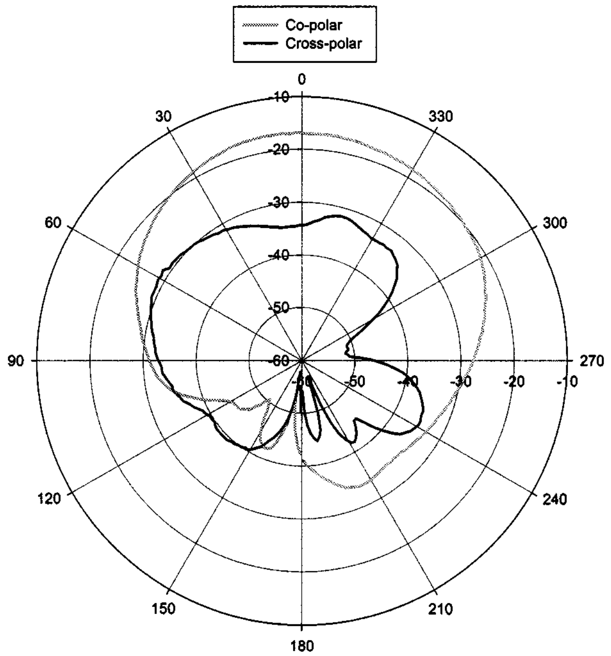


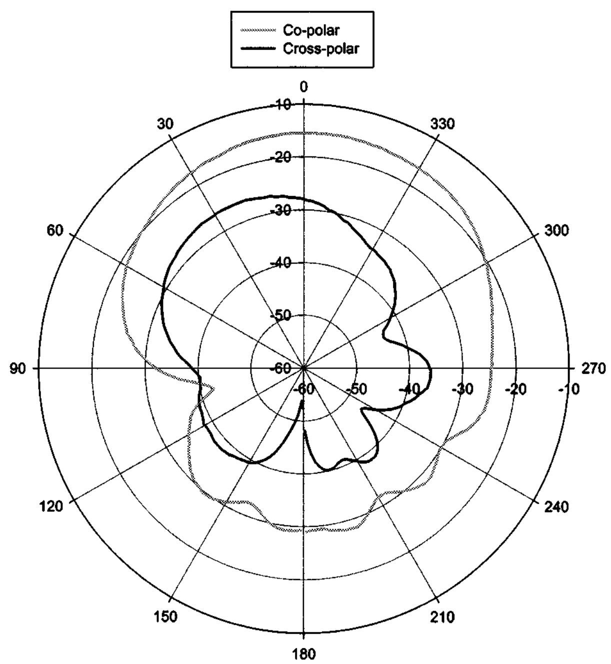
Fig. 9. (a) H-field co-polar and cross-polar plot (without probe). (b) H–field co-polar and cross-polar plot (with probe) (thick line is for the co-polar case).

C. Frequency Stability

There is a direct relationship between frequency stability and phase noise [11]. Fig. 8 shows the patch oscillator stability spectrum for both the locked and free-running conditions. The measurement is from a spectrum analyzer using the maximum



(a)



(b)

Fig. 10. (a) E-field co-polar and cross-polar plot (without probe). (b) E–field co-polar and cross-polar plot (with probe) (thick line is for the co-polar case).

hold facility over a 60-s period. The free-running instantaneous frequency drift is approximately 200 kHz in this time period, whereas the phase-locked plot shows no discernible drift.

D. Polar Diagrams

Radiation patterns for the patch antenna for both probe and nonprobe cases were measured in an anechoic chamber. The test chamber procedure is controlled by a PC and the signal is captured on a wide-band Vivaldi antenna. The signal is displayed on a spectrum analyzer (Hewlett–Packard 85671A). The spectrum analyzer is connected to a PC via an IEEE-488 interface to allow automatic collection of the data.

The insertion of the coaxial probe inevitably disturbs and modifies the polar diagrams, as shown in Figs. 9 and 10. In some directions, the fields are enhanced with the inclusion of the probe, and in other directions, are reduced and distorted. The most affected is the cross-polar E-field. A less intrusive method for sampling the antenna may be a microstrip tap with a dc block.

VIII. Conclusions

The free-running patch oscillator was seen to have extremely poor phase noise and stability. Substantial phase-noise reduction and effective patch oscillator frequency stability has been demonstrated by the use of PLL techniques, especially at offset frequencies close to the carrier.

The phase-noise measurement method is important. For the high noise associated with the patch antenna, the sophisticated delay-line discriminator method was necessary. A phase-noise improvement of the order of 55 dB resulted from this measurement method, whereas the spectrum analyzer method indicated just 26 dB.

The phase noise of free-running patch antennas is unacceptably high, but under PLL control, it becomes viable for use in commercial applications and compliant with international phase noise standards. A well-controlled active patch antenna lends itself to effective integration for use in future systems.

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John W. Andrews received the B.A. degree in mathematics and the B.Sc. degree from the Open University, Milton Keynes, U.K., in 1988 and 1995, respectively, and the Ph.D. degree from the University of Birmingham, Edgbaston, Birmingham, U.K., in 2000.

His industrial career includes a period in the Royal Air Force as a Radar Engineer, the Home Office Directorate of Telecommunications as a Senior Engineer, and from 1974 to 1993, he as a First Engineer with Midlands Electricity.

Peter S. Hall (M'88–SM'93–F'01) received the Ph.D. degree in antenna measurements from Sheffield University, Sheffield, U.K., in 1973.

He then spent three years with Marconi Space and Defence Systems, Stanmore, U.K., where he was largely involved with a European Communications satellite project. He then joined The Royal Military College of Science as a Senior Research Scientist and progressed to Reader in electromagnetics. In 1994, he joined the University of Birmingham, Edgbaston, Birmingham, U.K., where he is currently a Professor of communications engineering and Head of the School and Head of the Communications Engineering Group, School of Electronic and Electrical Engineering. He has extensively performed research in the areas of microwave antennas and associated components and antenna measurements. He has authored or co–authored four books, over 130 learned papers, and holds various patents. From 1991 to 1995, he was an Honorary Editor of the *Proceedings of the Institution of Electrical Engineering, Part H*, and is currently an Editorial Board member of the *International Journal of RF and Microwave Computer Aided Engineering* and *Microwave and Optical Technology Letters*.

Dr. Hall Professor Hall is a Fellow of the Institution of Electrical Engineers (IEE), U.K. He is a past chairman of the IEE Antennas and Propagation Professional Group and of the organizing committee of the 1997 IEE International Conference on Antennas and Propagation. He has been associated with the organization of many international conferences and was a member of the Technical Committee of AP2000 in Switzerland and was an overseas corresponding member of ISAP2000 in Japan. He was the recipient of six IEE Premium Awards, including the 1990 IEE Rayleigh Book Award for the *Handbook of Microstrip Antennas*.