A BROADBAND, SOLID STATE MILLIMETER-WAVE SYNTHESIZER

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A microprocessor controlled, low noise, millimeter-wave IMPATT frequency synthesizer has been developed. The IMPATT is phase locked to a crystal reference and covers greater than a 10 GHz band.

Summary

As the field of millimeter waves has progressed, so has the need for low phase noise, frequency agile, stable sources. In the past, this need has been filled by fixed frequency, phase-locked, solid state devices (IMPATT and Gunn oscillators)[1] or by phase-locked klystrons either at a fixed frequency or tunable over a very narrow bandwidth.[2] The following describes the development and operation of a broadband, low noise, millimeter-wave frequency synthesizer capable of covering more than a 10 GHz band in 750 kHz steps.

The solid state devices are, of course, more desirable than klystrons because of their reliability and longevity. An IMPATT oscillator is chosen over a Gunn because of its ability to be tuned over a vastly wider frequency range. A wideband, frequency tunable IMPATT (sweeper IMPATT) is necessarily more difficult to phase lock than a Gunn, klystron or fixed frequency IMPATT oscillator since the phase noise associated with the sweeper IMPATT is often an order of magnitude greater. Shown in Figure 1 is a typical phase-locking configuration. Figure 2(a) shows a typical RF spectrum of a "free-running" sweeper IMPATT. Whereas a loop bandwidth of 1 to 5 MHz is sufficient to phase lock a Gunn, klystron or fixed-tuned IMPATT, a sweeper IMPATT requires a loop bandwidth of 25 to 50 MHz.

Using wideband, hybrid op-amps, a loop bandwidth of 50 MHz is possible. In order to achieve this bandwidth, the IF section must be designed to minimize group delay. Group delay is manifested as phase shift at the higher frequencies of the error signal, thus decreasing the phase margin (and, therefore, the usable bandwidth) of the loop.

A major contributor to the group delay is the phase detector. Typically, a "quadrature mixer" is used (see Figure 3(a)). This device gives the cosine and sine of the phase angle between the IF and reference signals. One ouput is used as the loop error signal and the other is used to indicate whether or not a correct lock has been achieved (the lock alarm). Unfortunately, the unit causes relatively large phase shifts due to the hybrid power dividers used. To minimize the phase shift and still divide the signal correctly for sine and cosine processing, resistive dividers are used (see Figure 3(b)).

The other contributors to group delay are the IF amplifiers. Careful choice of amplifiers and good, closely spaced circuit layout minimize this contribution to the phase shift. Figures 2(b) and 2(c) show the spectrum of a phase-locked sweeper IMPATT. Figure 2(d) compares the phase-locked spectrum to the "free-running" spectrum. Significant improvement in the phase noise can be seen: 75 dB, 5 kHz from the carrier and 25 dB, 1 MHz from the carrier.

Another problem often encountered when phase locking an oscillator over a wide frequency range is variations in the oscillator's tuning sensitivity, K_o (rad/sec/ampere), over its frequency range, which causes equivalent variations of the loop gain. The gain may change as much as 10 dB with an

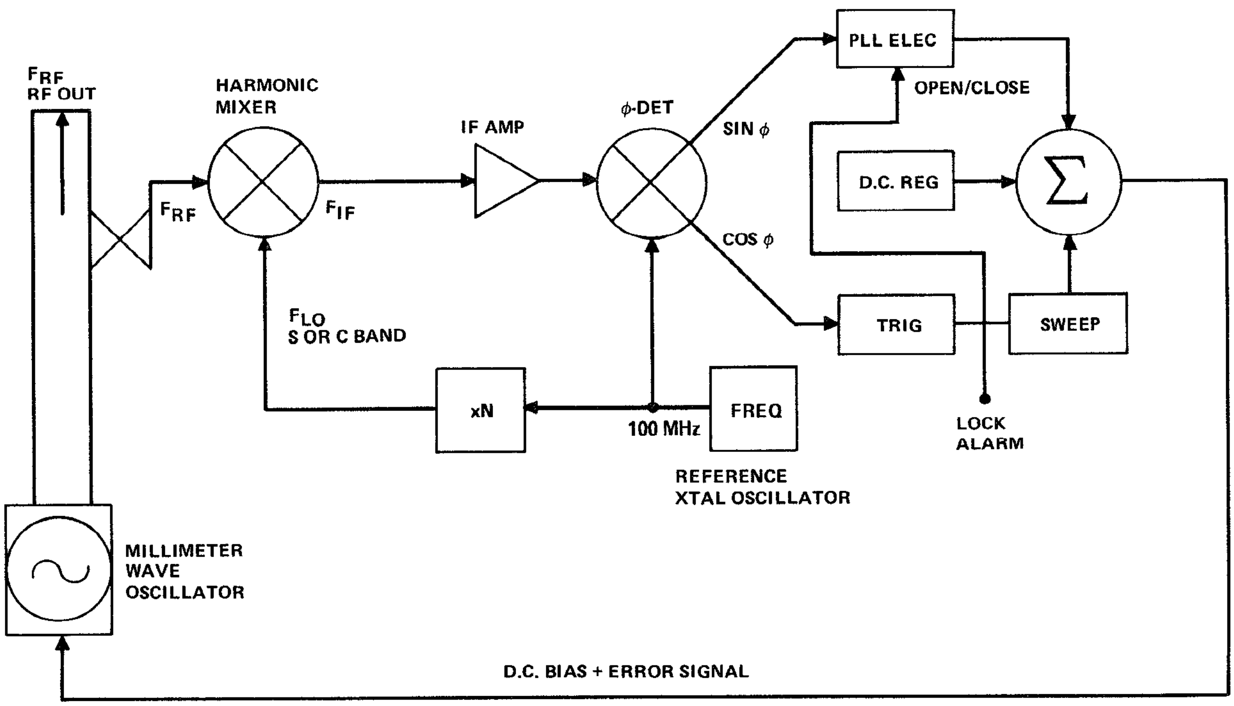
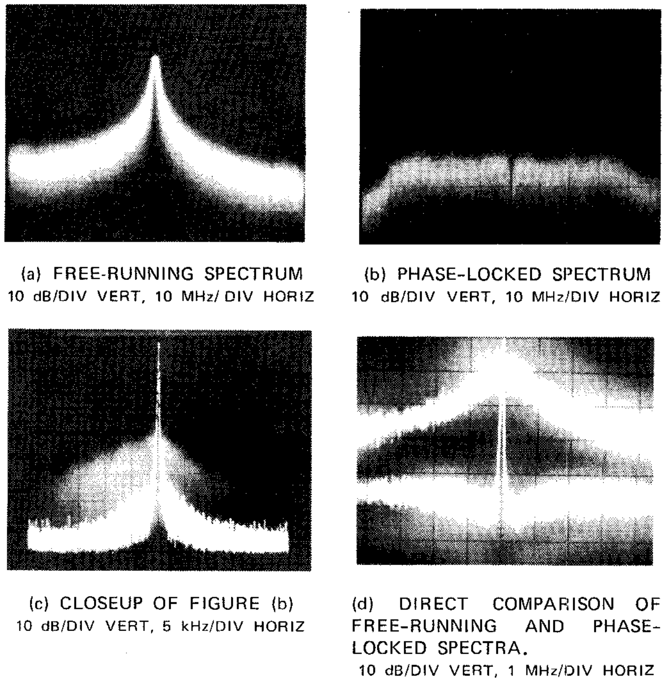


Figure 1. Basic block diagram of a millimeter-wave phase-locked loop.



(a) FREE-RUNNING SPECTRUM
10 dB/DIV VERT, 10 MHz/DIV HORIZ

(b) PHASE-LOCKED SPECTRUM
10 dB/DIV VERT, 10 MHz/DIV HORIZ

(c) CLOSEUP OF FIGURE (b)
10 dB/DIV VERT, 5 kHz/DIV HORIZ

(d) DIRECT COMPARISON OF FREE-RUNNING AND PHASE-LOCKED SPECTRA.
10 dB/DIV VERT, 1 MHz/DIV HORIZ

Figure 2. Spectra of W-band sweeper IMPATT

IMPATT oscillator, thus making stabilization of the loop difficult. The transfer function of a second order phase-locked loop (PLL) is:[3]

$$\frac{\phi_o}{\phi_i} = \frac{K_o K_d K_f (s + a)}{s^2 + K_o K_d K_f s + K_o K_d K_f a}$$

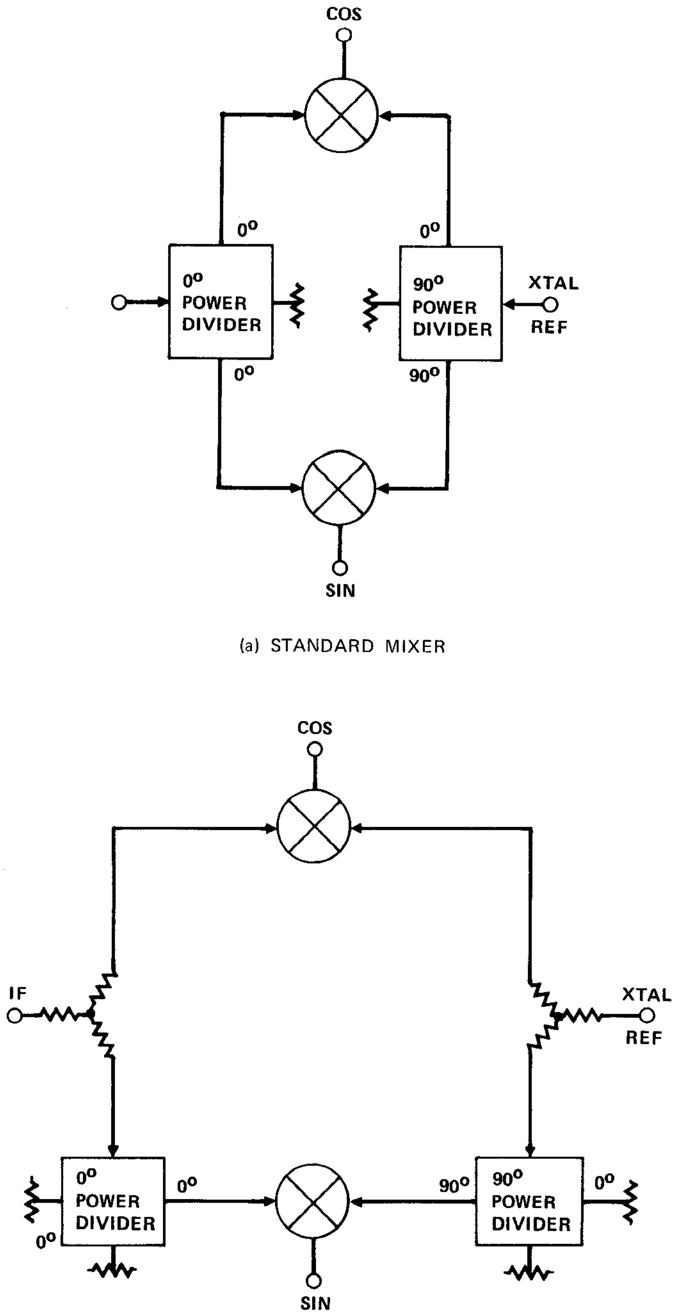
where the transfer function of the loop filter and amplifier is

$$F(s) = \frac{K_f (s + a)}{s}$$

and K_d is the transfer function of the phase detector (volt/rad). The loop is stabilized by inserting a programmable attenuator between the phase detector and the loop filter. This attenuator varies K_f inversely with K_o under microprocessor control, thus keeping the loop gain constant.

To automatically synthesize the various frequencies, a microprocessor is used to control the PLL. Shown in Figure 4 is a block diagram of the IMPATT millimeter-wave synthesizer. The operation of the microprocessor with the PLL is as follows: a desired frequency is input through the unit's keyboard or on the IEEE-488 bus. The microprocessor opens the loop. Using look-up tables in PROM memory, the bias current is adjusted with the sweep control signal, the LO frequency is set, and the gain is adjusted with the programmable attenuator. If the RF signal is within 10 MHz of the desired frequency, the lock alarm signals the microprocessor to hold the sweep control (and thus the quiescent current of the IMPATT) at its present level. The loop is closed and lock is achieved. If the RF frequency is not correct (due to thermal drift, etc.), the microprocessor sweeps the bias current until the RF signal is within 10 MHz of the desired frequency. The lock alarm then causes the microprocessor to hold the sweep level constant and closes the loop.

The switching time from one phase-locked frequency to another is less than 10 msec. The step size is from 550 to 750 kHz. Typical single-sideband phase noise specifications are: -65 dBc/Hz, 1 kHz from the carrier; -75 dBc/Hz, 5 kHz from the carrier; -85 dBc/Hz, 25 kHz from the carrier; and



(a) STANDARD MIXER

(b) MIXER WITH RESISTIVE DIVIDERS

Figure 3. Quadrature mixture configurations.

-90 dBc/Hz or better, 100 kHz from the carrier and beyond. The output power will typically be +3 dBm (2 mW) or greater.

Conclusion

With the capability of a microprocessor controlled, phase-locked sweeper IMPATT covering a 10 GHz bandwidth having been developed, this conceptually simple phase lock idea makes possible a crystal referenced millimeter-wave synthesizer having the low phase noise and stability required of a true frequency synthesizer. This technique will open the door for a wide range of applications in both instrumentation, such as a full waveguide-band synthesizer, and in a variety of EW systems, such as frequency agile coherent radars and secure communications.

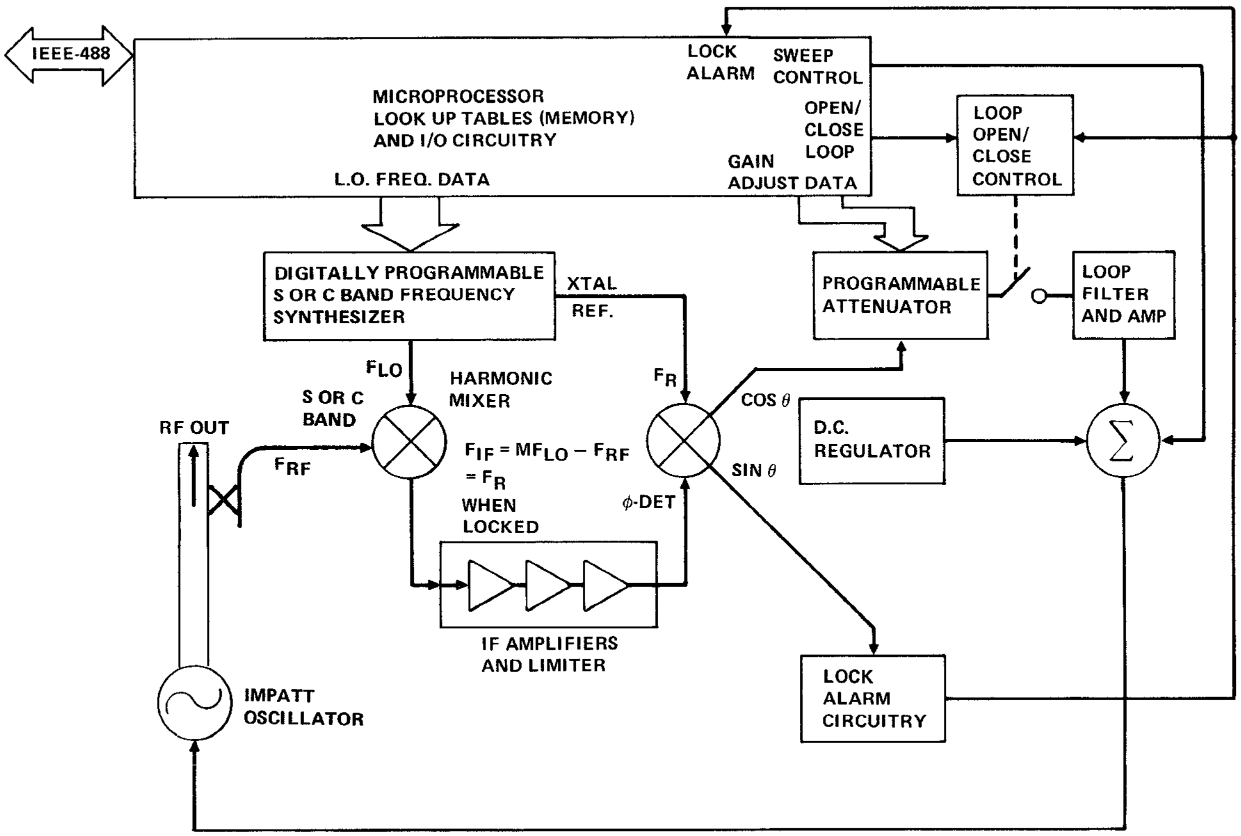


Figure 4. Synthesizer block diagram.

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References

1. J. Baprawski, C. Smith and F. J. Bernues, "Phase-Locked, Solid State, Millimeter-Wave Sources," The Microwave Journal, October 1976.
2. P. S. Henry, "Frequency Agile Millimeter-Wave Phase Lock System," Review of Scientific Instruments, September 1976, pp. 1020-1025.
3. S. Wetenkamp, "Combating Phase-Lock Loop 'Transportation Lag'," MSN, March 1978, pp. 101-106.