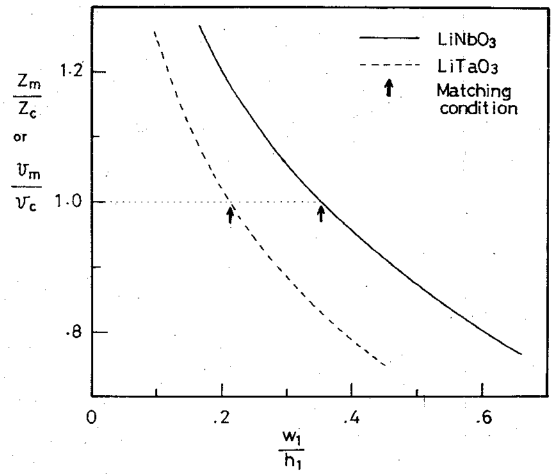

Fig. 2. Numerical results to indicate dimensions to satisfy the two matching conditions for the case of $LiNbO_3$ and $LiTaO_3$ crystal.

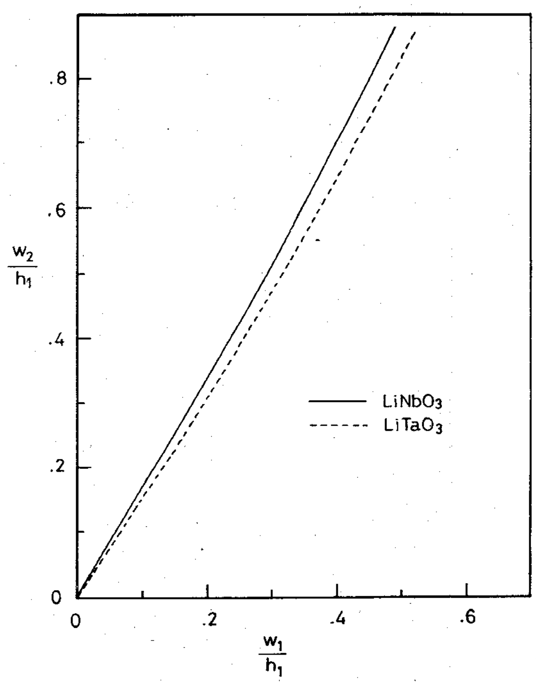

Fig. 3. Relation between the two widths W_1 and W_2 for the case of $LiNbO_3$ and $LiTaO_3$ crystal.

thus achieved, the final bandwidth of a modulator using a quasi-TEM line is limited by the dispersion characteristics at high microwave frequencies.

Note Added in Proof: The length and the transverse dimension of traveling-wave modulators will eventually be limited by the diffraction effect of the laser beam [1], [2]. This limitation is also important in order to achieve the modulation with minimum power/bandwidth.

ACKNOWLEDGMENT

The authors wish to thank Prof. T. Okabe for his helpful advice and E. Kiuchi for his assistance.

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A MIC Phase-Locked Loop Avalanche Oscillator in X Band

J. SALMON

***Abstract*—This short paper describes the design and performances of a MIC phase-locked loop X-band avalanche oscillator. The output power (500 mW/CW), the input reference level (1 mW), the locking time (80 ns), and the simplicity of digital phase control makes it very attractive as a primary element of an active phased array.**

INTRODUCTION

Solid-state active phased arrays have always appeared attractive in radar applications. First, because the inherent losses of the passive phased array (more than 3 dB on signal at high microwave frequencies) are avoided, and second because these arrays are probably the best way to realize a powerful solid-state transmitter. However, these arrays can be expected to achieve industrial applications in radar only if the structure of each element is not too sophisticated.

Two approaches to solid-state arrays were considered until now. In the first approach, phase shifting and amplification were achieved at a lower frequency (S band, for instance, in the MERA [1]) and a high-power multiplier provided the right frequency. In the second approach phase shift and amplification were directly achieved at the right frequency. In both cases, phase shifting was made by quantified microwave phase shifters at low level, and amplification was made either by transistor or diode amplifiers (multistage). Altogether, that makes a great number of microwave (expensive) components.

The phase-locked loop (PLL) oscillator seems to be an economical way to realize high microwave gain, especially in X band and above. In addition, quantified phase control can be achieved easily by commutation at video frequencies instead of microwave phase shifters. The study presented below is the first step in the realization of an active element of an X-band phased array.

THEORETICAL BACKGROUND

The PLL principle is shown in Fig. 1 [2]. A portion of the signal provided by the voltage controlled oscillator (VCO) on one side and the reference on the other side enters a phase detector (PD). The output signal of that PD is sent through the baseband amplifier to the frequency control (varactor) of the VCO.

For a PLL, frequency synchronism is achieved throughout a band B when we have the following:

B G_oKS.
G_o Baseband amplifier (BBA) gain.
K Characteristic slope of the PD (V/rad).
S VCO's control characteristic (MHz/V).

For the system under study, the technical requirements were: minimum synchronization bandwidth $B = 30$ MHz; reference signal power: 1 mW (which leads to a PD characteristic K of 0.3 V/rad

Manuscript received May 14, 1973; revised August 2, 1973. This work was supported by the Service Technique des Télécommunications de l'Air under Contract 70/86 050
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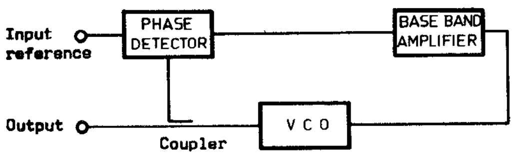

Fig. 1. PPL principle.

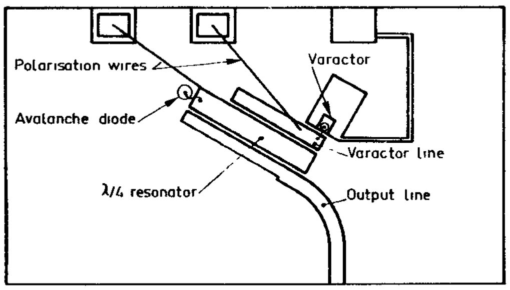

Fig. 2. Diagram of VCAO.

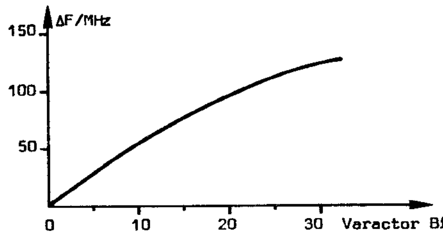

Fig. 3. Voltage control characteristic.

as we will see further).

The resulting characteristic of the BBA and VCO are

$$G_o = 20 \text{ (26 dB)}$$

$$S = 5 \text{ MHz/V}.$$

Stability is obtained when overall phase shift of the loop is less than 180° in the 1-dB bandwidth [3].

DESIGN

The system is designed to be inserted into a phased array that needs a cross section smaller than half a wavelength square (exactly 1.8- by 1.8-cm in X band [4]). Consequently, thin and thick film technology had to be chosen.

Voltage Controlled Avalanche Oscillator (VCAO)

The MIC VCAO is shown in Fig. 2. An Si avalanche diode chip is mounted at the end of a $\lambda/4$ low impedance resonator. This resonator is coupled on one side to another resonator tuned by the varactor and on the other side to the 50-Ω output line. An S characteristic of 5 MHz/V is obtained by tight coupling of the varactor. The results are a loss of power of 1 dB and a reduction of the Q factor. The correlative temperature sensitivity had to be compensated by insertion of Titania on the $\lambda/4$ resonator.

The final characteristics of the VCO are: central frequency: 9.3 GHz; bandwidth of electronic tuning: 150 MHz (Fig. 3); control characteristic slope more than 5 MHz/V; the output power is greater than 500 mW for an input power of 11 W; the frequency drift in the temperature range $-40° + 71°$C is equal to 15 MHz.

Phase Detector (PD)

The PD is a classical MIC balanced mixer that uses Schottky barrier diodes. Fig. 4 presents the schematic view of this PD.

A portion of the VCO signal (P_{OL}) is used as local oscillator (strong signal). The reference signal is sent at the other end. Fig. 5 shows the video output voltage versus reference signal power P_R for different P_{OL}. A slope of 0.3 V/rad was chosen, which corresponds to $P_{OL} = 2.5$ mW and $P_R = 1$ mW. With these conditions the bandwidth of the PD is greater than 300 MHz. The bandwidth of the microwave circuits (phase and amplitude) are given in Fig. 6.

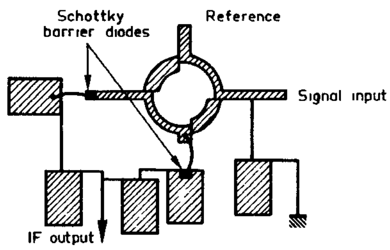

Fig. 4. Phase detector.

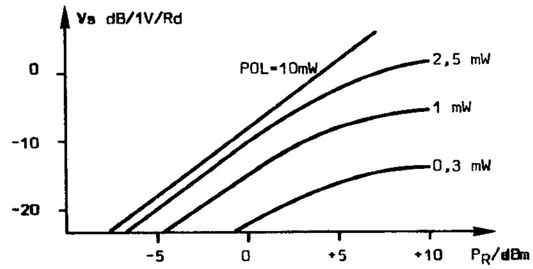

Fig. 5. Video output of PD versus reference level.

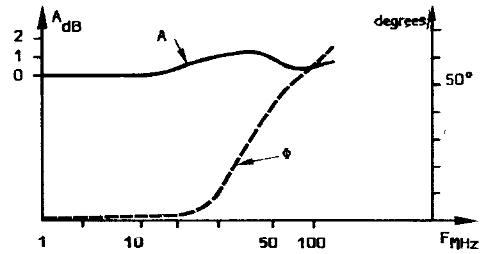

Fig. 6. Bandwidth of the microwave circuits.

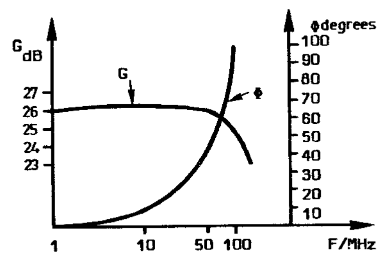

Fig. 7. Gain/phase BBA performances.

Baseband Amplifier (BBA)

To meet the bandwidth requirements, this amplifier has to provide an output voltage of 10 V peak to peak from 0 to 50 MHz with a gain of 26 dB. If we consider the phase-amplitude characteristics of the microwave circuits (Fig. 6), the stability is securely obtained if the phase shift in the 0-dB bandwidth does not overcome 45° (an additional phase shift of 90° being due to the integration in the loop [2]).

A two-stage differential amplifier was adopted to get those very high performances. We chose two 2 N 2857 at the input and four 2 N 4261 at the output. The differential input allows, by simple commutation, an inversion of the phase of the locked position (i.e., a 180° phase shift). The differential output makes the achievement of dynamic characteristics easier. Fig. 7 gives the amplitude and phase response of the BBA versus frequency.

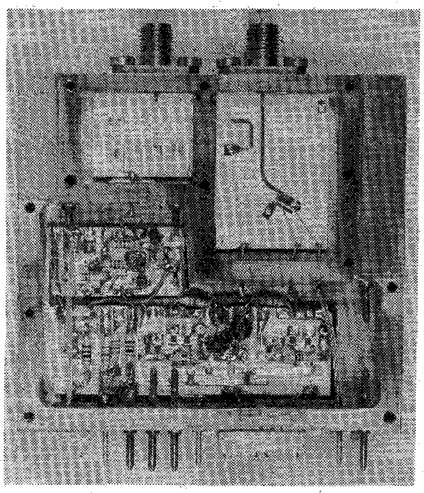

Fig. 8. Phase-locked loop oscillator.

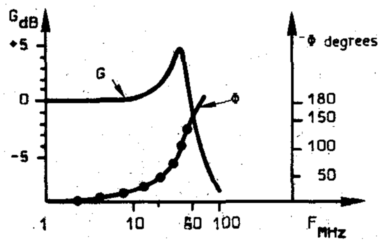

Fig. 9. Gain/phase PLO performances.

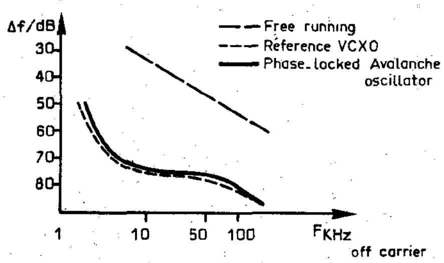

Fig. 10. FM noise in 1-kHz bandwidth.

PHASE-LOCKED LOOP RESULTS

The three elements were connected as shown in Fig. 8. For the study's flexibility of the BBA, thick film technology was chosen in order to be able to adjust some elements and also to include discrete components. The total results in the whole temperature range ($-40°$, $+71°$C) are as follows: reference signal input level: 1 mW; synchronization time for ± 20 MHz offset: 80 ns; maximum synchronization frequency offset: ± 30 MHz; and output level: 500 mW.

The transfer function in closed-loop operation was measured by injecting an error signal in the symmetrical input of the differential BBA. The results are shown in Fig. 9 (note a global 3-dB bandwidth of 57 MHz). The transformation in the Black–Nichol's diagram [5] shows a phase "margin" of 35° and a gain "margin" of 9 dB. This allows a good stability in series production.

The reference being a low noise VCXO, the FM noise was measured by phase detection between the output of the avalanche oscillator and another low noise VCXO signal. The results (Fig. 10) show that the phased-locked loop avalanche oscillator (PLLAO) is compatible with Doppler radar applications [6]. Free running FM noise is presented on the same figure to show the drastic improvement brought about by phase locking

APPLICATION TO ACTIVE PHASED ARRAYS

The PLLAO described can be easily phase controlled by video (low price) commutation between PD and BBA, with the arrangement shown in Fig. 11. This figure is the schematic diagram of a 2-bit phased-array elementary source.

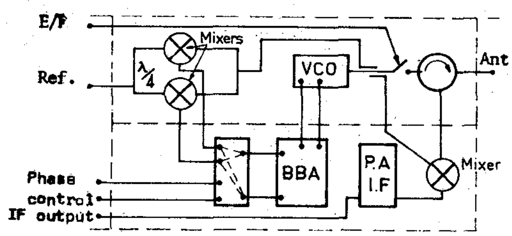

Fig. 11. Element diagram.

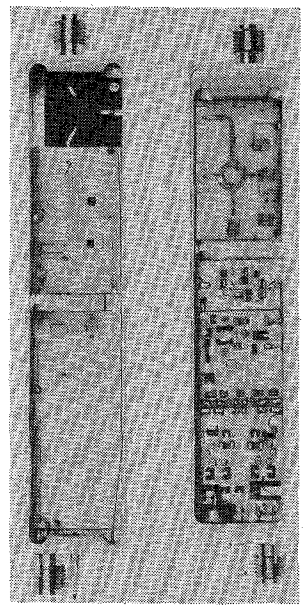

Fig. 12. Active-phased array element.

The fixed-phase reference is sent to two PD's with a differential phase shift of 90°. The output of one of these is selected by a logic control, and sent to one input of the BBA. By changing on one end this input, and on the other end the PD selected, one can lock the VCO on four phase positions 90° apart.

The VCO is used as the transmitter with a duty cycle of 0.5. During the reception it is used as local oscillator. Reference frequency and phase control are changed between transmission and reception. A mockup of this element is shown in Fig. 12.

On this figure, we can see on the first side, the circulator, the VCO, the two PD's, and on the other side the BBA, the phase logic control, and the mixer and IF preamplifier.

CONCLUSION

The excellent performances obtained on the PLLAO, its aptitude to an easy digital phase control, and its low noise properties open a new path in the active phased arrays field. In fact, competitive applications in radar will be really considered only with the development of high-efficiency avalanche diodes (GaAs) which can be expected in a few years.

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