A MMIC BASED INJECTION LOCKED OSCILLATOR FOR OPTICALLY FED PHASED ARRAY ANTENNAS

T. Berceli, A. S. Daryoush, P. R. Herczfeld, W. D. Jemison, A. Paolella

Center for Microvave-Lightwave Engineering
Drexel University
Philadelphia, PA 19104

ABSTRACT

In an optically fed phased array antenna system, the microwave carrier signal is transmitted via a modulated lightwave to each active T/R(transmit/receive) module where it must be converted back to the microwave domain. Currently, efficient optical to microwave conversion is extremely difficult as the detected microwave signal is weak and noisy. A novel circuit, containing a high gain - low noise microwave injection locked oscillator, has been developed to improve the interface between the optical and microwave components. The circuit utilizes two FET's and a dielectric resonator which serves as a frequency dependent feedback element. The circuit provides significant amplitude and phase noise suppression and is designed to operate around 10GHz. In addition the circuit realization is fully compatible with MMIC technology.

INTRODUCTION

A new generation of phased array antennas will utilize a large number of individually powered MMIC (monolithic microwave integrated circuit) T/R (transmit/receive) modules. The frequency and phase synchronization of each T/R module is critical in assuring array coherence. In an optically fed phased array antenna system coherence is accomplished by the distribution of the reference (microwave carrier) signal to each T/R module via high-speed fiberoptic links[1-3]. The reference signal is utilized for both up and down conversion of information at the T/R module[4] and must have adequate phase stability, noise performance, and sufficient power to drive the mixers of the T/R module. The optical signal, which carries the RF reference, is weak and noisy particularly at higher frequencies[5] and circuitry is therefore required to provide an efficient interface between the optical feed and the T/R module microwave circuitry. The primary purpose of this circuitry is to convert the optical signal into a strong, clean microwave signal.

A reference circuit for an optically fed phased array antenna is shown in Fig. 1. The intensity of a lightwave modulated by a microwave reference signal at the CPU (central processing unit) is distributed via a fiber optic network to each T/R module. The intensity modulation may be performed by either a high-speed laser or an external electro-optic modulator. The microwave reference signal is then directly detected at each element by a highly sensitive PIN diode. Then the power level of the recovered microwave reference signal has to be enhanced. A novel circuit has been designed and built utilizing an injection locked oscillator to serve as an interface between the optical feed and the T/R module microwave circuitry for this purpose. The circuit design criteria are high gain, high frequency and phase stability (high Q-factor), high AM(amplitude modulation) and FM (frequency modulation) noise compression, and MMIC implementation.

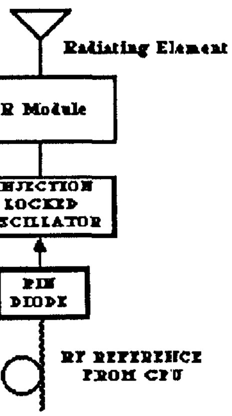

Fig. 1 Block diagram of RF reference circuit including the injection locked oscillator.

CIRCUIT DESCRIPTION

The schematic block diagram of the circuit is shown in Fig. 2. The circuit utilizes two chip transistors operated as wideband amplifiers. Port 1 serves as the input for the injection locking signal which originates from the PIN detector. Port 2 is the output of the oscillator which is fed to the LO (local oscillator) input of the T/R module mixers. The dielectric disc resonator serves as a frequency dependent feedback element which determines the free running oscillation frequency. The function of the matching circuits is to provide efficient coupling between the PIN detector and the input of the oscillator, as well as between the oscillator output and the T/R module mixers. It should be noted that efficient matching of the PIN to the first transistor requires special consideration and was not considered in this work.

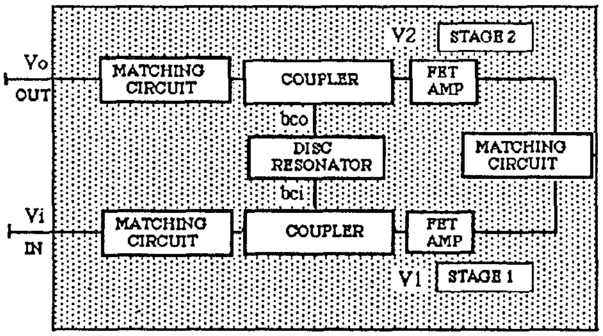

Fig. 2. MMIC compatible injection locked oscillator circuit.

Several advantages are realized in the present design configuration. The two stage approach enhances the output power of the oscillator while providing good noise performance even at low injection levels. This is accomplished by using a low noise HEMT or FET in the first stage in order to minimize the noise of the oscillator. The first stage is operated as a nearly linear amplifier and its bias is adjusted according to the low noise requirement such that the drain current is only 15-20% of its saturation value. In the second stage, a high gain FET is operated in a nonlinear mode to increase the oscillator output power level and also to limit the oscillator amplitude. In addition, the two stage design requires lower injected signal power for a given locking band than a single stage design due to its increased gain.

The present design also offers advantages in the oscillator noise performance.The design provides significant AM compression due to the high gain of the injection locked oscillator. In addition both amplifiers are designed to operate over a much wider band than the locking band so they will not introduce frequency dependence around the desired oscillation frequency. The oscillation frequency is therefore determined by the resonant frequency of the high Q dielectric disc whose higher order mode resonances are well above the fundamental mode resonance. In addition, high phase stability can be expected over a wide temperature range due to the inherent temperature stability of the dielectric disc resonator[6].

It should also be noted that the present design requires only standard MMIC transistors and passive components (capacitors and no inductors) and is therefore totally compatible with MMIC technology. A circulator is not required as the input and output ports are separated and the application of a circulator would be superfluous. MMIC implementation is important for T/R module compatibility as well as economy in a large phased array application.

THEORETICAL INVESTIGATION OF THE DOUBLE TRANSISTOR INJECTION LOCKED OSCILLATOR

A nonlinear circuit analysis was performed to determine the expected circuit performance. Investigations were performed for both the free running and injection locked modes of operation. Specifically, it was desired to investigate the AM compression and AM to PM conversion to determine the optimum operating point for the circuit with respect to noise performance[7].

The simplified circuit block diagram shown in Fig.2 was used for the analysis. Voltage control is assumed in the analysis[8] consistent with the FET implementation such that only the fundamental voltage appears at each port. The overall port voltages of the amplifier stages are designated by V_1 and V_2, and are all assumed to be real quantities. Furthermore, b_{ci} is the voltage coupling factor at the input, b_{co} is the voltage coupling factor at the output, and Q_e is the external Q-factor of the dielectric disc resonator where the loss of the dielectric resonator is neglected in the feedback circuit. Both amplifiers are considered to be nonlinear for completeness.

The overall voltage transfer function for the two amplifiers may be obtained as:

$$V_2 = A_0\left(1 - n_3V_1^2\right)V_1 \qquad (1)$$

Only two terms of the general power series description of nonlinear networks have been retained for simplicity. A_0 is the small signal voltage gain, n_3 is the coefficient of the third power term.

The transfer function of the dielectric resonator is also required and is given as follows:

$$F = F_r + jF_i = \frac{1 - j2Q_e\delta}{1 + (2Q_e\delta)^2} \qquad (2)$$

where F_r is the real part and F_i is the imaginary part of the transfer function, Q_e is the external Q-factor of the resonator, and δ is the relative frequency deviation from the resonant frequency f_0 as defined below:

$$\delta = \frac{f - f_0}{f_0} \qquad (3)$$

In general, the voltage at Port 1 consists of both feedback and injected voltage components and may be expressed as:

$$V_1 = V_2b_c(F_r + jF_i) + V_{ir} + jV_{ii} \qquad (4)$$

where b_c is the overall voltage feedback coupling factor which is simply the product of the input and output coupling factors: $b_c = b_{ci}b_{co}$. $V_i = V_{ir} + jV_{ii}$ is the voltage of the injected signal, and V_2 is given in Eq. (1). Equation (4) is valid for operation in the locking band where the operating frequency is determined by the frequency of the injected signal.

Free running oscillation

First, the case of free running oscillation is considered. The free running case is characterized by the absence of the injected signal such that $V_{ir} = V_{ii} = 0$ and the free running oscillation frequency is equal to the resonant frequency of the dielectric disc. Substituting V_1 from Eq(4) into Eq(1) the voltage V_{20} is expressed as:

$$V_{20}^2 = \frac{A_0b_c - 1}{A_0n_3b_c^3} \qquad (5)$$

from which the condition of oscillation is obtained:

$$b_c > \frac{1}{A_0} \qquad (6)$$

The feedback coupling factor must be greater than the reciprocal of the voltage gain for oscillation.

Injection locked oscillator

Next, the injection locked mode of operation will be considered where the injected voltage is a complex quantity as previously mentioned. The real part of Eq.(4) may be substituted into Eq.(1) to obtain a third order expression for V_2:

$$V_2^3\left(n_3A_0b_c^3F_r^3\right) + V_2^3\left(3n_3A_0b_c^2F_r^2V_{ir}\right) + V_2\left(3n_3A_0b_cF_rV_{ir}^2 - b_cF_rA_0 + 1\right) - A_0V_{ir} + n_3A_0V_{ir}^3 = 0 \qquad (7)$$

The phase difference, θ, between the injected signal and the feedback signal may now be found by solving the imaginary part of Eq.(4) such that:

$$\Theta = \tan^{-1}\left(\frac{-V_2b_cF_i}{V_{ir}}\right) \qquad (8)$$

Finally the powers are normalized to the maximum power of the free running oscillator. The normalized input and output powers are denoted by small letters: p_i and p_2.

The locking band can be determined based on Eq. (4). If the phase shift, θ, is equal to π/2 then the real part of the injected voltage V_{ir} will be zero and the voltage V_2 will be the same as in the case of the free running oscillator. The locking band then becomes:

$$B_L \approx \frac{f_0}{Q_eb_c}\sqrt{\frac{p_i}{p_o}} \qquad (9)$$

The locking band is inversely proportional to the feedback coupling factor b_c which is again inversely proportional to the voltage gain A_0. An increased locking band may therefore be obtained by increasing the voltage gain and properly choosing the feedback coupling factor b_c. The advantage of the increased gain capability of the double transistor injection locked oscillator is thus obvious.

Nonlinear transfer properties

The nonlinear transfer property of the injection locked oscillator is described by its derivative characteristics. It is desired to achieve high AM compression which is a function of the voltage gain, feedback coupling factor, and injected voltage.The AM compression of the novel injection locked oscillator is plotted in Fig. 3 at band center (δ = 0) for different coupling factors as a function of the normalized injected power.

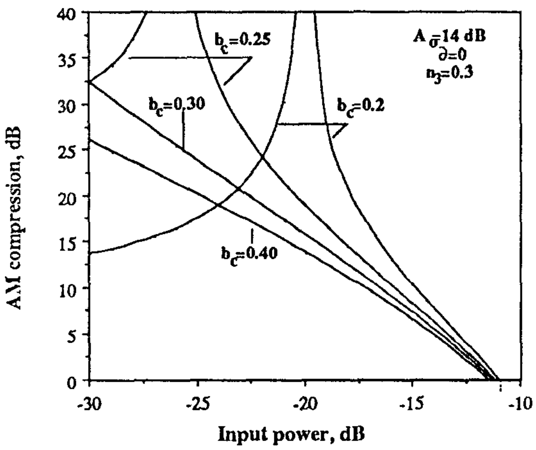

Fig. 3 AM compression vs. injected power

The voltage gain is 14 dB for the plot corresponding to the designed circuit gain and maximum output power is obtained with $b_c = 0.3$ in the free running mode of operation. As seen, a higher AM compression can be reached at if the feedback coupling factor is less than this value. Therefore, a looser coupling is desired to provide increased AM compression.

EXPERIMENTAL CIRCUIT CONSTRUCTION

The circuit is constructed in a hybrid MMIC/ microstrip construction to operate around 10 GHz. Since matching to the PIN diode was not considered in this effort, the circuit was designed with standard 50 ohm terminations and connections. A circuit simulation was performed using Touchstone and greater than 14 dB of gain was predicted for the two amplifiers. The circuit layout is shown (although not to scale) in Fig. 4. Two general purpose chip FET's were utilized for both Stage 1 and Stage 2. Although these devices will not provide as good a noise figure for Stage 1 as a HEMT, the noise figure of the FET's is adequate for initial investigations. The position of the dielectric disc is movable, and by this way the coupling factor can be varied experimentally.

CONCLUSION

A novel circuit, containing a high gain - low noise microwave injection locked oscillator, has been developed to improve the interface between the optical and microwave sub-assemblies of optically fed phased array antennas. The circuit utilizes two FET's and a dielectric resonator which serves as a frequency dependent feedback element. The circuit provides significant amplitude and phase noise suppression and has been designed to operate around 10GHz. In addition the circuit realization is fully compatible with MMIC technology.

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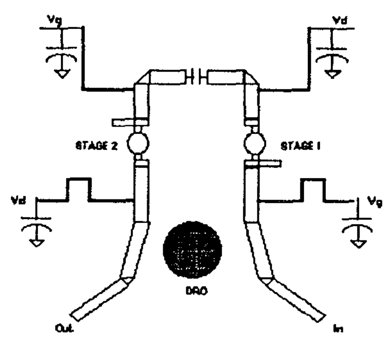

Fig. 4 CAD circuit layout