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PHASE AND FREQUENCY COHERENCY OF MULTIPLE OPTICALLY SYNCHRONIZED 20GHZ FET OSCILLATORS FOR SATELLITE COMMUNICATIONS

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ABSTRACT

Future generation of communication satellites are based on large aperture phased array antennas, which are composed of many active transmit/receive modules. The phase and frequency coherency of these modules are of concern. A viable technique to provide phase and frequency references for synchronization is through fiber-optic distribution and using indirect subharmonic optical injection locking techniques. Experimental results of phase and frequency coherency of two 20GHz FET oscillators are reported in this paper. Optimum performance was achieved at subharmonic factor of 1/4 with locking range of 84MHz and phase noise degradation of only 14 dB. Initial phase coherency measurements of two injection locked oscillators indicate that a phase error can be introduced due to the detuning between the slave and master oscillator signals. A scheme to correct for this phase error is also presented.

INTRODUCTION

Future generation of communication satellites, operating at up-link of 40GHz and down-link of 20GHz, are designed based on a large number of MMIC transmit/receive (T/R) modules to configure an active phased array antenna. Key to these applications is the frequency and phase synchronization of the distributed, independent T/R modules. Phase and frequency coherency of individual modules are mandate for spatial power combining and coherent communication systems. Various techniques to provide synchronization of active T/R modules have been proposed, from all viable techniques high-speed fiber-optic distribution networks are receiving most attention [1]. However, bandwidth of fiber-optic links are presently limited by the optical modulators and it is not anticipated that laser diodes with bandwidths in excess of 20GHz will be available in the near future. The approach pursued to achieve frequency synchronization is the indirect optical injection-locking of local oscillators using laser diode nonlinearity [2]. Large-signal modulation of semiconductor lasers provides higher order harmonics of the modulating frequency and thereby extend the effective bandwidth of the fiber-optic links [3-5]. Using this technique, feasibility of frequency synchronization of an IMPATT oscillator at 38.9GHz has been demonstrated [6].

Present work is concerned about the phase and frequency coherency of two optically injection locked FET oscillators at 21.5GHz. First, design of FET oscillators will be discussed. Second, results of subharmonic indirect optical injection locking of FET oscillators will be presented for different subharmonic factors. These results will be compared and criteria for optimization will be outlined. Finally, phase coherency measurement results will be presented.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1, where two 21.5GHz FET oscillators are optically synchronized to a reference source. An ultra high-speed buried hetero-junction (BH) GaAlAs laser diode, manufactured by Ortel Corp., is used in this experiment as an optical source. The fiber pigtailed laser diode package emits light at 810nm and has an output power of 4.5mW out of the fiber end. The laser diode has a threshold current of 17mA and is biased by an optical power monitered power supply to maintain constant output power. The 3dB bandwidth of the laser diode is 9.3GHz at biasing level corresponding to 90% of maximum output power. Laser diode is large-signal modulated at f_o by a synthesized source through a bias-Tee. The modulated light output is coupled to 3dB optical coupler from Canstar with coupling coefficient of 47% and 43%. Light in the first arm of coupler is collimated using a 0.25 pitch selfoc lens and is focused on a high-speed pin photodiode by a short focal length lens from Melles Griot. The output from the second arm of the coupler is spliced to 100m of graded index multimode fiber, where is wrapped around a pieze-electric (pzt) crystal 150 times. The light is then detected by a high-speed pigtailed pin photodiode. The pin photodiodes are manufactured by Ortel Corp. and have 3dB bandwidths of 14GHz. The responsivity of photodiodes are 0.45mA/mW, and 0.35mA/mW at 840nm for 20V reverse biasing respectively. The detected fundamental and harmonics (i.e. f_o, $2f_o$, $3f_o$) of the master source are amplified in both arms by broadband (6-12GHz) amplifiers from Avantek. Amplification gain stages of either 25dB or 50dB can be introduced using two ac coupled amplifiers. The amplified signals are then injected to the free running FET oscillators at 21.5GHz through broadband (1-26.5GHz) directional couplers from Krytar in place of circulators. The output of the injection locked oscillators are monitored on a spectrum analyzer using external mixers.

The approach to measure phase coherency of the two injection locked oscillators is to compare phase of one with respect to another on the network analyser test set. Output of the oscillator #1 is fed to reference port of the test set and the signal from oscillator #2 is provided to the port 2 of the test set. When the oscillators are locked, super heterodyne detection provides the phase difference between the reference (oscillator #1) with respect to the test signal (oscillator #2). In order to examine the phase coherency of the injection locked oscillators the pzt ring is utilized as a varible phase shifter. The pzt crystal has a diameter of 9.6cm and radial strain factor of of $(\Delta C/C) = 10^{-2}$ ppm/V, where C is the circumference of the ring. The capacitive breakdown voltage of the pzt crystal is calculated to be as high as 4KV. A high voltage dc supply provides the biasing voltage for expansion of the pzt ring, hence causing the fiber to stretch. This expansion introduces a variable time delay (i.e. phase shift) for the phase of the reference signal [7]. The phase shifting by the piezo-electric stretcher follows the simple relation:

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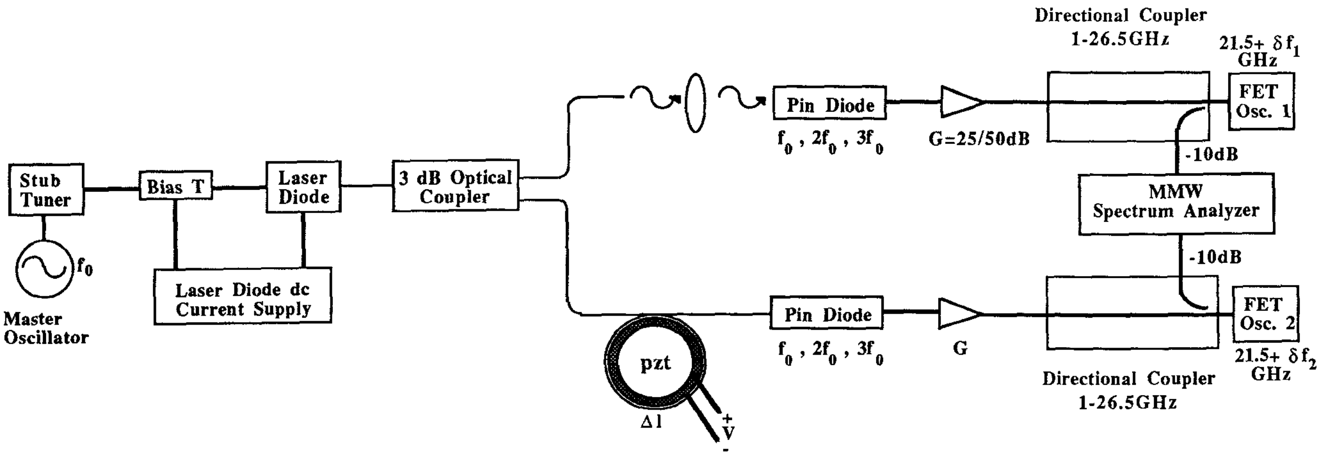


Fig. 1. Experimental setup for frequency synchronization of two FET oscillators at 20GHz. Thin lines corresponds to optical fibers and thicker lines refer to electrical connections. The pzt ring is used for examining of phase coherency between two injection locked oscillators.

$$\Delta\Phi = 2\pi(\Delta l/\lambda_g) = 2N\pi^2 D*10^{-5}*V/\lambda_g$$

where $\Delta\Phi$ is the phase shift in radians, Δl is the stretching introduced in the fiber, λ_g is the guide wavelength of the microwave modulating envelope of the optical carrier, N is the number of turns, D is the diameter of the pzt ring, and V is the dc applied voltage in KV. Using this variable phase shifting, a phase shift will be introduced in the synchronizing signal which will be transferred into a phase shift in the output of oscillator #2.

20GHZ FET OSCILLATOR DESIGN

The 20GHz free-running oscillators were designed and fabricated using low noise 0.5μm GaAs MESFETs from Avantek. The FET oscillators, realized on alumina substrates in a hybrid form, were self biased at 50% of I_{dss} using chip voltage regulator of 8 volts. The biasing conditions were: V_{ds}= 4 volts and V_{gs}= -1 volt for I_{ds}=45mA. The I_{ds} was adjusted with the bias resistance in the source as shown in the Fig. 2. Using the transistor model and microwave CAD program, the value of series feedback capacitance was determined to optimize the negative resistance around the desired frequency of 21.5GHz. A microstrip open circuited stub in the gate was adjusted to satisfy oscillation frequency at 21.5GHz. A matching stub on the drain was used primarily to maximize the output power. The output power of 10mW was measured at 21.55GHz . The power spectrum of the free-running oscillator is shown in Fig. 3a. A good pushing factor of 100kHz/V was obtained for the oscillator due to the stable dc biasing provided by the voltage regulator. The external Q of the free-running oscillators were determined by direct electrical injection locking and is calculated to be 205, using Adler's locking range equation [8].

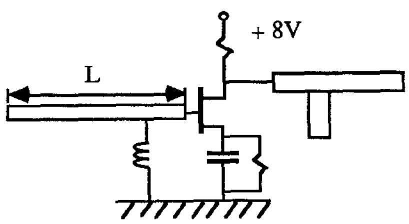


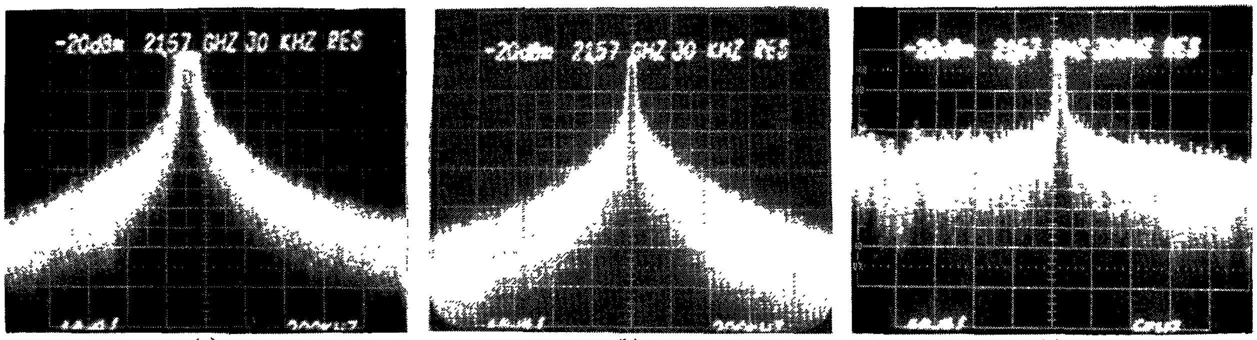
Fig. 2. Simplified layout of the 21.5GHz FET oscillator.

EXPERIMENTAL RESULTS

In the injection locking of two slave oscillators, nonlinear multiplications in laser diode and FET were exploited [3]. More specifically, when the BH laser diode was large-signal modulated by 8dBm signal from synthesized master source at frequencies of 3.593, 5.389, and 10.779GHz, the harmonics were generated in the laser diode [4, 5]. In particular, the signal at 10.779GHz was filtered out and amplified by the cascaded amplifier stage. The amplified signal was then subharmonically injected to the 21.5GHz FET oscillators. Therefore, a multiplication factor of 2 was attained in the FET; and based on the modulating frequency which was employed, multiplications factors of 3, 2 and 1 were obtained in the laser. More explicitly from master oscillator point of view, injection locking was occurred at subharmonics of 1/6, 1/4, 1/2 respectively (i.e. 3.593GHz*3*2= 21.558GHz, 5.389GHz*2*2= 21.558GHz, 10.779*1*2= 21.558GHz). Spectrum of the free-running FET oscillator before and after injection locking by the 5.389GHz signal from master oscillator, are shown in Fig. 3. A close in spectrum of the injection locked FET oscillator is shown in Fig. 3c, where a phase noise of -57dBc/Hz at 1kHz offset carrier was measured. The locking range of the FET oscillators were also examined. For 50dB amplification gain, a locking range of 12MHz was attained for subharmonic of 1/2 (i.e. modulating frequency of 10.779GHz). However, for the modulating frequency of 5.389GHz (subharmonic of 1/4) a locking range of 84MHz was achieved. The spectrum of the injection locked oscillator prior, during and after injection locking is shown in Fig. 4.

Performance of the injection locked oscillators in terms of figures of merit, such as locking range and FM noise degradation of the master source, were studied. The result of comparison for subharmonic factors of 1/6, 1/4, 1/2 and amplification gain of 25dB, is shown in Table I. In these experiments the laser diode dc biasing was adjusted at each modulating frequency to optimize the attainable locking range for a constant 8dBm input rf power (i.e., optical modulation depth was adjusted for best results). These results point out to three subtle issues:

i) Large-signal modulation of lasers is an important technique to achieve optical synchronization of oscillators at frequencies above 10GHz [3].
ii) Large-signal modulation of lasers is optimum at frequencies which are close to the large-signal relaxation oscillation frequency [4, 5].



(a) (b) (c)

Fig. 3. Spectrum of the FET oscillator #1 at 21.5GHz; a) Free-running (horizontal scale of 200KHz/div.), b) indirect subharmonic optical injection locked to 5.389GHz signal (horizontal scale of 200KHz/div.), c) Locked (horizontal scale of 5KHz/div.). These results are for amplification gain of 25dB.

iii) A compromise between FM noise degradation and locking range should be made.

The phase coherency of the two injction locked oscillators were also examined. The phase shift introduced by the pzt crystal was first studied. Phase shifts up to 40^o at 10GHz were attained, which were linearly dependent on the dc biasing voltage. However, initial experiments indicated that phase coherency of the injection locked oscillators could not be preserved. To correct for this phase error, techniques based on injection locked phase locked loop are recommended[4].

DISCUSSION

Two FET oscillators at 21.5GHz were fabricated on alumina substrate using hybrid techniques with a very low pushing factor. These free-running oscillators were subharmonically synchronized to a synthesized reference signal through a fiber-optic link. Locking range of 84MHz was achieved for subharmonic factor of 1/4 with respect to the master source. The multiplication factors of 6, 4, and 2 were attained using laser diode and FET nonlinearities. The performance of the injection locked oscillators were evaluated from locking range and FM noise degradation figures of merit, and subharmonic locking using factor of 1/4 was preferred over 1/6 and 1/2. Phase coherency of the injection locked oscillators were also examined. Initial results indicates that phase of the injection locked oscillators does not remain coherent and their phase is dependent on the frequency detuning factor. Therefore, approaches such as injection locked phase locked loop [4] should be considered.

A collective vision of this paper and previous reported work, points to three subtle issues for optimum indirect subharmonic injection locking. The foremost result is that large-signal modulation of laser diode is the key for optical injection locking of millimeter wave oscillators [5]. Second, the modulating frequency should be in the proximity of the large-signal relaxation oscillation frequency [4]. Third, amplitude of the relaxation oscillation frequency is very critical in the detected harmonics amplitude. The final point is mainly laser structure dependent, and requires a careful selection of laser diodes for actual implementation.

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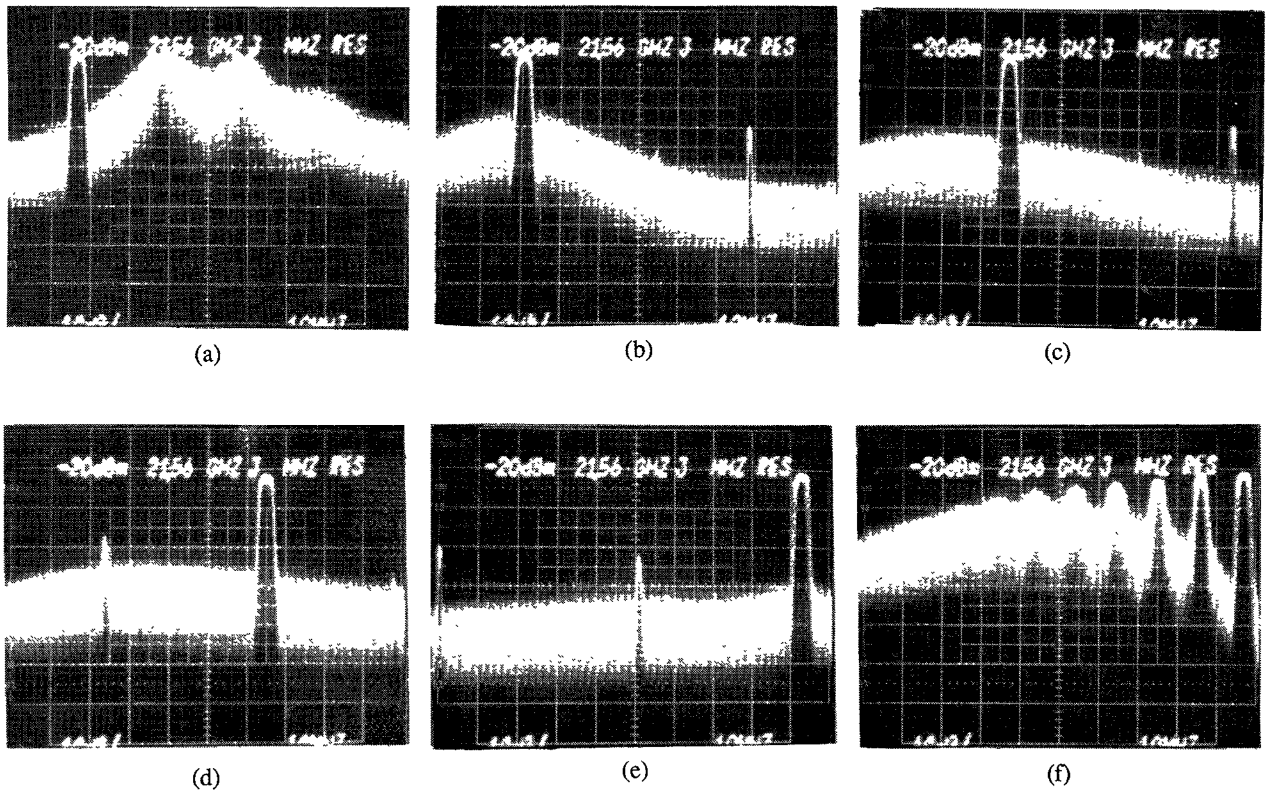

Fig. 4. Master-slave pulling range of the FET oscillator #1 for twenty one 1MHz steps of master source. (Horizontal scale at 10MHz/div and vertical scale of 10dB/div.) a) 5.375GHz (begining of locking with sidebands), b) 5.376GHz (locked), c) 5.380GHz (locked), d) 5.387GHz (locked), e) 5.394GHz (locked), f) 5.395GHz (end of locking with sidebands).These results are for amplification gain of 50dB and subharmonic factor of 1/4.

Modulating Freq. f_0 (GHz)	Biasing Current I_b (mA)	Locking Range Δf (KHz)	FM Noise Degradation at 1KHz Offset (dB)
3.593	22	≈800	≈13
5.389	32	1600	≈12
10.779	42	≈400	≈4

Table I. Comparison of the locking range and FM noise degradation of 21.5GHz FET oscillator #1 for three different subharmonic factors of 1/6, 1/4, and 1/2. The rf input power to laser diode is kept constant at 8dBm for all frequencies, while the laser dc bias is adjusted for maximum pulling range. The FM noise degradation is measured with respect to the master oscillator signal at the modulating frequencies of 3.593GHz, 5.389GHz, 10.779GHz.