PHASE CONTROL OF OPTICALLY INJECTION LOCKED OSCILLATORS FOR PHASED ARRAYS

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ABSTRACT

Future generation of space-based communications systems are envisioned to employ high-speed fiberoptic links for distribution of control and communication signals. The most suitable architecture for millimeter wave frequencies are based on the *T/R level data mixing* architecture, where a frequency reference is provided to local ocillators in the subarrays to have them frequency and phase sysnchronized. The indirect subharmonic optical injection locking has benefit of high degree of frequency synchronization up to millimeter wave frequencies, however they suffer from phase inaccuracy over the locking range, first formulated by Adler. In this paper we propose a scheme to measure this phase error and correct for by adjusting the free-running oscillation frequency of a VCO. Experiments supporting this approach are reported for two optically injection locked oscillators at 18GHz, where controlled phase shifts over -90° to 78° are achieved by adjusting the bias current to a YIG tuned VCO.

INTRODUCTION

Future generation of space-based communication platforms satisfying broad bandwidth, rapid beam reconfigurability and hopping, and low cost requirements, are designed based on optically controlled millimeter wave active phased array antennas (1). Fiber optic distribution of millimeter wave signals to active transmit/receive (T/R) modules is an essential part of coherent operation of large aperture phased array antennas (2). Between the two possible architectures of *CPU level data-mixing* and *T/R level data-mixing* (3) proposed for optical feed to the active elements, the latter technique is the most viable method ensuring highest bandwidth (4) and dynamic range (5). Therefore, we envision that phased array antenna architectures operating above 10GHz will be designed based on concept of two separate groups of fiber optic feeds: the first class are ultra high-speed fiberoptic links for distribution of carrier signal that are typically in high microwave frequency regime; and the second class are to distribute the communication and control signals, which are typically up to Gbps range.

Challenging problem of optical feed of frequency synchronization at millimeter waves can be addressed using either injection locking or phase lock loop (PLL) techniques of local oscillators (6), each with its own limitations. The injection locking provides the highest synchronization frequency with phase shifts in the range of $\pm \pi/2$ over the locking range, whereas PLL provides excellent phase and frequency synchronization with limitation of maximum obtainable frequency. In fact injection locking is most applicable method at millimeter wave frequencies, particularly subharmonic injection locking was demonstrated up to 40GHz (2), and it is anticipated that using parametric oscillations in nonlinear active devices, frequency synchronization of oscillators can be extended to 60 and 94GHz range. Nevertheless, since each module of the phased array has independent local oscillator and each operate at different free-running oscillation frequency, the unwanted phase shifts produced by frequency detuning of independent local oscillators with the frequency reference will introduce pointing inaccuracy of the radiating beam. To overcome problem of phase incoherency of injection locked oscillators, a technique of phase correction is recommended, which is combination of injection locking and PLL known as injection locked PLL (ILPLL) (7).

Goal of the present work is to demonstrate feasibility of ILPLL scheme at 18GHz leading to correction for the phase errors caused by the frequency variation of two independent local oscillators. Furthermore, concept of analog phase shifting based on controlling the frequency detuning of the free-running oscillators is presented, which could be employed as a high resolution phase shifter in beam steering of phased array antennas.

EXPERIMENTAL SET UP

Conceptual representation of experimental set up for the phase compensation and shifting at carrier frequency of 18GHz is rendered in Fig. 1. In this approach frequency reference at 4.5GHz is distributed to two free-running oscillators at 18GHz using a high-speed reference fiberoptic link. The frequency reference at 4.5GHz is inputted to a custom designed optical transmitter. The optical transmitter in this experiment is based on an ultra high-speed buried hetero-junction (BH) GaAlAs laser diode mounted on a heat sink (Ortel SL1000H) with a reactive matching network at 4.5GHz ± 100MHz, thermo-electric cooler, an optical monitoring circuit. The biasing current and the input rf power is adjusted such that the current modulation index of 1.3 is achieved, so the large-signal relaxation oscillation frequency would be shifted to the driving frequency at 4.5GHz. Under the large-signal modulation close to relaxation oscillation frequency, substantial harmonics levels of the modulating signal are generated (8). Particularly, the operating conditions were optimized for the second harmonic, such that highest power level at at 9GHz was achieved in expense of the fundamental frequency. Therefore, the frequency reference was multiplied by a factor 2 inside the laser diode (i.e., 4.5GHzx2=9GHz).

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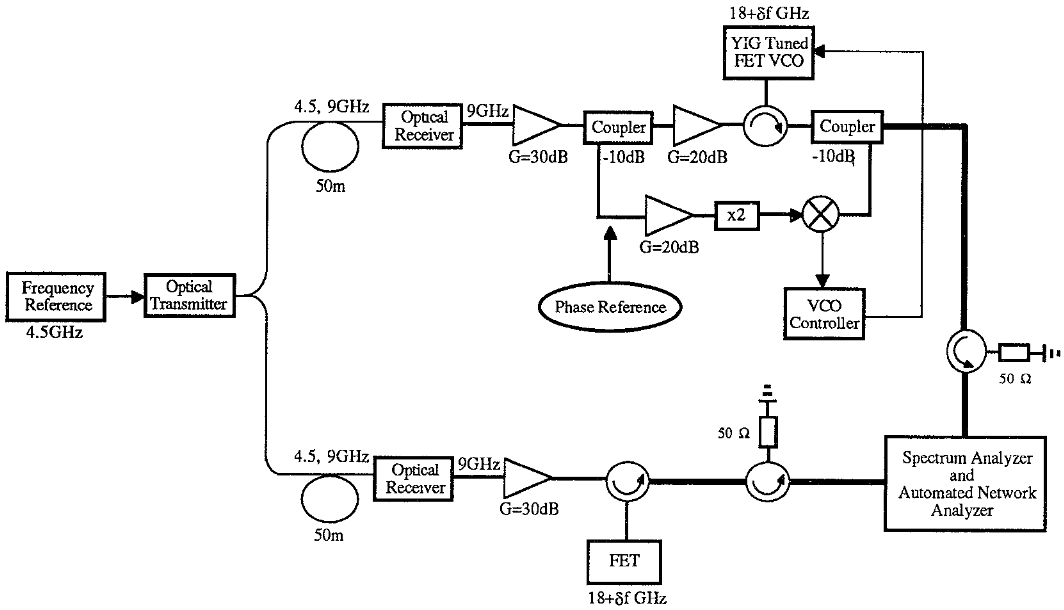

Fig. 1 Experimental setup for the study of phase and frequency coherency of two subharmonic optically injection locked FET oscillators at 18 GHz. The VCO is used to study the proposed scheme for phase correction and phase shifting of the local oscillator in phased array antennas.

The optical transmitter output is a multimode fiber with biconic optical connector and is coupled to an optical coupler from Canstar, with coupling factors of 53% and 38% respectively. The divided optical powers are then coupled to two optical receiver after transmission through 50m of multimode (50/125μm) optical fibers. The modulated light in the first path is coupled tthrough a 0.29 pitch GRIN lens to a AlGaAs heterojunction pin photodiode, which is reactively matched at 9GHz. The second path is used for comparison and is detected by a commercially available optical receiver, which is not matched to 50Ω.

The detected signals at 9GHz are amplified and then used to subharmonically injection lock two FET based local oscillators at 18GHz. In this regard, another multiplication by factor two of frequency reference occurs in the nonlinear oscillators (i.e., 9GHzx2=18GHz). In this experimental set up, the oscillator #1 is a YIG tuned voltage controlled oscillator (VCO) with output power of 13dBm. This oscillator is incorporated to a ILPLL circuit so phase and frequency synchronization to the master reference signal at 9GHz is assured. On the other hand, the oscillatror #2, a free-running FET oscillator with output power of 6dBm, is only frequency synchronized to the frequency reference of 9GHz. The spectral power of the oscillators are observed on a Tektronix 492 spectrum analyzer. To monitor the phase shifts caused by fequency detuning of the slave oscillator, the injected signal at 9GHz is amplified by 20dB and then coupled to a frequency doubler realized using a varactor diode to convert 9GHz frequency reference to 18GHz. The output of the doubler at 18GHz is high-pass filtered and its phase is compared with the phase of the injection locked oscillator #1.

Two types of phase correction circuits were used. The systrem was calibrated by HP8511A harmonic convertor test of HP8510B automatic network analyzer. However, from practical view point as part of the PLL circuit, a standard mixer (Avantek DBX184L) was used. The IF port of the mixer was monitored on a oscilloscope or dc voltmeter. This connfiguration of mixer, lowpass filter and dc voltmeter constitutes the phase comparator. As long the oscillator 1 is injection locked to the master oscillator, the IF output is a dc voltage, however for regions outside locking range, the IF output of the mixer is a low freuency signal. The dc voltage is function of the phase difference between the reference signal at 18GHz and the oscillator #1. The output of the phase comparator is inputed to the VCO controller. Thus, any phase shift caused by frequency detuning of the oscillator can be used to adjust the free-running oscillation frequency of the YIG tuned VCO.

EXPERIMENTAL RESULTS

The FET oscillators were biased for output powers of 10dBm and 3dBm and corresponding frequencies of 18.0115 and 18.0135 GHz were measured on the spectrum analyzer respectively, as shown in Fig. 2. When the synthesized master oscillator was set at 4.502846GHz, the oscillators #1 and #2 were synchronized, as shown in Figs. 3 and 4 respectively. Next locking range of the oscillators were examined. As shown in Fig. 5, a locking range of 26MHz was obtained for oscillator #1 whereas for the oscillator #2 only a 2MHz locking range was attained. The fundamental reason behind this small locking range of the oscillator #2 is the lower injected power at 9GHz. This can be corrected by use of reactively matched receiver at 9GHz and higher amplification gain stage in the synchronization path of the oscillator #2.

Next the phase corection scheme was investigated. First the phase coherency of the free-running FET oscillator #2 was examined. In this experiment the automated network analyzer (HP8511A harmonic convertor) was used to compare the phase of the reference signal at 18GHz (i.e., master oscillator signal of 4x4.5GHz) with the oscillator #2 output. Over the locking range of this oscillator, phase shift of 178° was observed for the swept

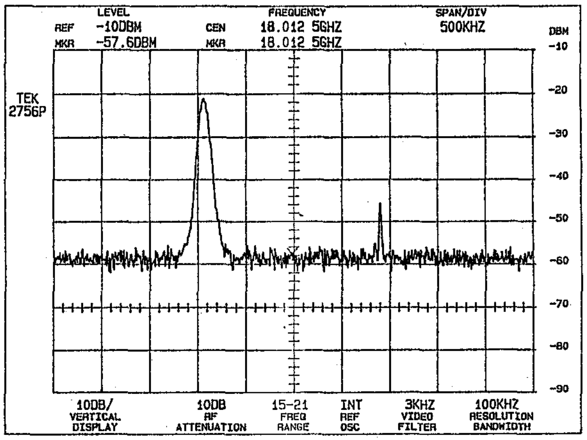

Fig. 2 Spectrum of the two free running oscillators before injection locking observed on spectrum analyzer based on the experimental setup. The left trace is the free running FET (Po= +6 dBm) and the right trace is the YIG tuned VCO (Po= +13 dBm).

master oscillator signal. This experimental result corresponds to the theoretical expectation of ±90° (9). To calibrate the phase shift introduced by the oscillator #1, the phase of the reference signal was compared with the output of the injection locked oscillator #1, and for each phase measurement the dc voltage associated with the beat signal was measured on the oscilloscope. This output voltage then corresponds to the phase difference introduced because of frequency detuning of the swept master oscillator and the oscillator #1. The same experimental result of ≈±90° was observed over the locking range of 26MHz.

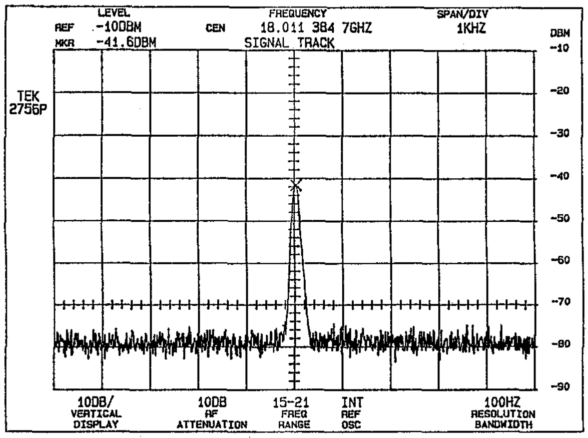

Fig. 3 Spectrum of the optically injection locked oscillator #1 (YIG tuned VCO) synchronized to 4.502846 GHz frequency and phase reference.

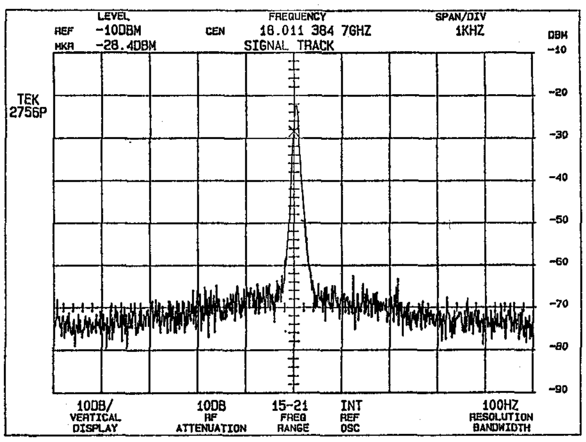

Fig. 4 Spectrum of the optically injection locked oscillator #2 (free running FET oscillator) synchronized to 4.502846 GHz frequency and phase reference.

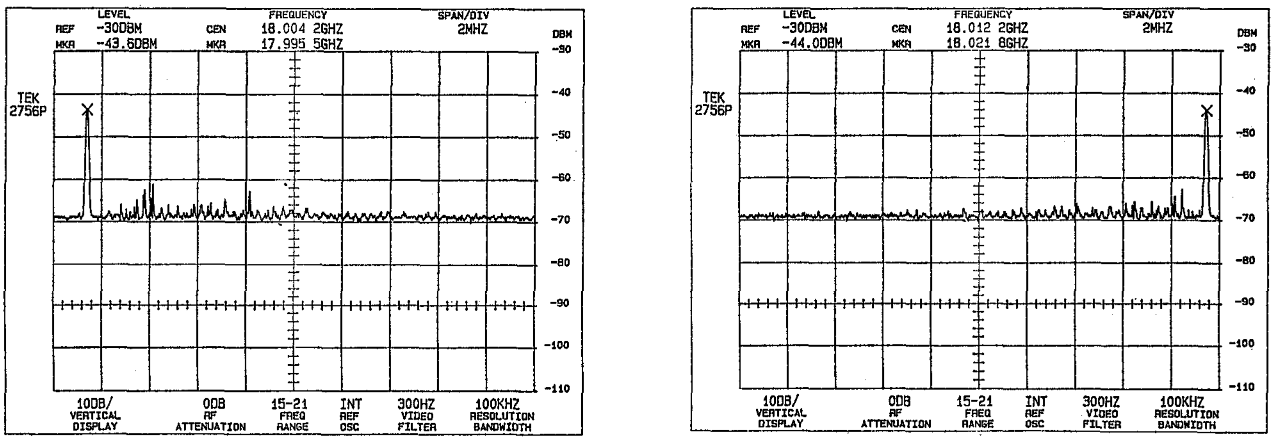

Fig. 5 Locking range of the YIG tuned VCO at 18 GHz; a) beginning of locking with side bands to the right of pulled oscillator (fo= 4.498916 GHz), and b) end of locking with sidebands to the left of pulled oscillator (fo=4.505283 GHz).

To demonstrate the phase correction of the ILPLL technique, frequency of the master oscillator was kept at 4.502846GHz and phase difference between the phase of the reference signal and the injection locked oscillator #1 was measured. If a dc voltage - different from zero, which corresponds to the in phase measuremt - was measured at the IF output of the mixer, then the free-running oscillation frequency of the VCO was altered by adjusting the bias current in the YIG crystal. This adjustment at the present is performed manually, however it demonstrates the feasibility of this concept. Next the phase control of the injection locked oscillator #1 was examined using the control of the bias current to the YIG crystal. Experimental result of this control approach is shown in Fig. 6, where phase shifts of -90° to +78° were measured.

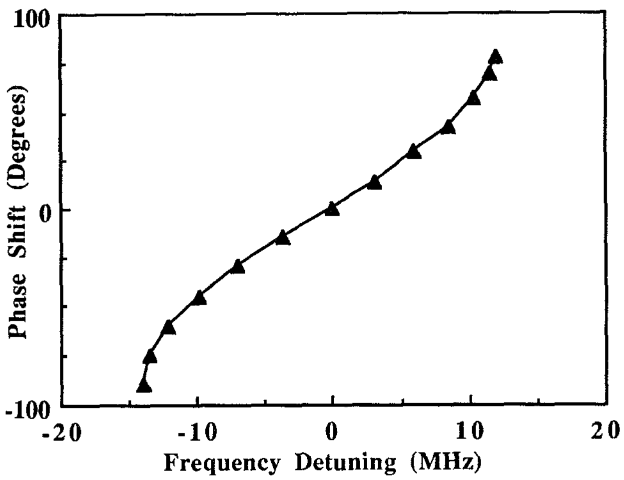

Fig. 6 Phase shift is introduced by detuning of the slave VCO from the fixed master's oscillator's frequency reference at 4.502846 GHz. The solid deltas correspond to data points within the locking range, where as the solid curve is as result of the theoretical expectation from Adler's model. The frequency detuning is achieved by adjusting the bias current to the YIG crystal in the YIG tuned FET oscillator circuit.

DISCUSSION

The ILPLL technique was proposed for the optically injection locked oscillators to overcome the phase shift introduced as result of the frequerncy detuning of the injected signal and the free-running oscillator. Particularly, experimental results of the ILPLL technique at 18GHz was demonstrated. This technique assures phase and frequency coherency of remotely located local oscillators in distributed antenna structures.

The phase dependence of injection locked oscillator on the frequency detuning over the locking range can be exploited for beam steering of phased array antennas. Since oscillation frequency of each free-running local oscillator can be tuned using a varactor diode, controlled phase shifts in the range of ±90° can electronically obtained over the locking range for each VCO. In principle, the VCO can tune the free-running oscillation frequency to a desired frequency, detuned from the injection locking frequency, such that the desired analog phase shift over the phase range of $\pm\pi/2$ is obtained. However, close to the ends of locking range the phase noise increase dramatically, hence limiting the usable phase shifting only to the center of the locking range. For example, frequency detuning cvausing phase shifts in the range of ±45° would have very small impact on the close-in carrier FM noise levels. Furthermore, adding a 2bit phase shifter (i.e., phase shifts of 0 , $\pi/2$, π and $3\pi/2$) would result in the full analog phase shifts of 0 to 2π. Advantages of this technique are many. Particularly, by integrating all of these components on a single chip, not only a coherent frequency reference is established, but also analog phase shifts with high degree of phase accuracy is obtained. This scheme of phase shifting will also reduce size of the active T/R modules, because the high resolution phase shifters (like 6 bits and above) are the longest component in the MMIC based T/R modules.

These initial results are very promising and additional work are planned in the near future. To improve efficiency of this system a regenerative frequency halver rather than frequency doubler is proposed. Even though multiplier and divider circuits are implemented using nonlinear characteristics of FET, but the former technique requires power amplification of the frequency reference, whereas the latter technique relies on the high output power of the injection locked local oscillator.

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