FIBER OPTIC LINKS FOR MILLIMETER WAVE COMMUNICATION SATELLITES

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ABSTRACT

Large aperture phased array antennas operating at millimeter wave frequencies are designed for space-based communications and imaging. Array elements are comprised of active transmit/receive (T/R) modules which are linked to the central processing unit through a high-speed fiberoptic network. This paper demonstrates optical control of active modules for satellite communication at 24GHz. An approach called *T/R level data mixing*, which utilizes fiberoptic transmission of data signal to individual T/R modules to be upconverted by an optically synchronized local oscillator, is demonstrated at 24GHz. In this study free-running HEMT oscillator, used as local oscillator at 24GHz, is synchronized using indirect subharmonic optical injection locking over a locking range of 14MHz. Results of data link performance over 500-1000MHz is also reported in terms of gain-bandwidth, linearity and third order intercept, sensitivity, and dynamic range.

INTRODUCTION

Large aperture phased array antennas will play an increasingly important role in communications and surveillance. Such antennas, utilizing large numbers of monolithic microwave integrated circuit (MMIC) components, offer the flexibility to handle the demand for rapid beam-hopped variable area coverage used in airborne and space-based applications. Control of large number of distributed transmit/receive (T/R) modules requires low loss, light weight, interference free, and broad bandwidth characteristics of fiber-optic (FO) distribution networks (1). Potentially this network in conjunction with optical signal processing provides for full control of active elemens. In particular, distribution of phase and frequency synchronization signals, to maintain coherency of the active modules, and transmission of data are two important functions of FO links.

A technique to assure frequency synchronization of the T/R modules is the indirect subharmonic optical injection-locking of local oscillators (LO) (2) using the nonlinear characteristics of laser diodes (3). This paper reports on optical synchronization of free-running HEMT oscillators operating at 24GHz by a master oscillator at 6GHz. Furthermore, performance of reactively matched laser sources, designed for distribution of 0.5-1GHz data, is compared to the resistively matched optical transmit modules. Finally, a communication network at K-band is established by upconverting the data signal by the stabilized 24GHz LO. This technique is called a *T/R level data mixing*.

EXPERIMENTAL APPROACH

The experimental arrangement, shown in Fig. 1, demonstrates FO distribution networks to obtain 0.5-1GHz bandwidth data signals at carrier frequency of 24GHz out of two active T/R modules. There are two separate categories of fiber optic links in this setup. The first category provides the frequency reference from CPU to two local oscillators at the T/R modules for the purpose of frequency synchronization. The second class is dedicated to data transmission for upconversion by the stabilized local oscillators. The upconverted data signals at 24GHz are then coupled to the MMIC based T/R modules for power conditioning before coherent radiation.

The frequency reference is distributed to two seperate T/R modules using a high-speed semiconductor laser diode, fiber optic power splitter, and two high-speed detectors. A high-speed AlGaAs buried heterojunction (BH) laser diode (Ortel TSL1000) with a 3dB bandwidth of is large-signal modulated by a synthesized source at 6GHz (C-band). Large-signal modulation of the laser diode for the frequencies in the proximity of the large-signal relaxation oscillation frequency, results in a distrorted light output with high harmonics content (4). This in turn increase the effective bandwidth of the FO link.

The modulated light output of the laser diode is split by a 3dB optical coupler from Canstar (PC3-C-50) and then transmitted through 50m long multi-mode graded-index fiber (50/125μm) from Siecor. The frequency reference at 6GHz and its harmonics are then detected by two high-speed AlGaAs heterojunction PIN photodiode receivers (RS025). The PIN photodiodes have a 3dB bandwidth of 15GHz with responsivity of 0.35A/W. In particular, the second harmonic of the master oscillator at 12GHz is amplified and filtered out by 35dB gain amplifier from Avantek. This reference signal is injected electrically to the free-running oscillators. The oscillators are HEMT based and operate at 24GHz with the output power of ≈10dBm. The subharmonic injection to the slave oscillator is through a circulator. However, since 12-24GHz circulators are not commercially available a 1-26.5GHz 10dB coupler from Krytar is used with 10dB penalty. The subharmonic injection locking will occur at 24GHz with the subharmonic factor of 1/2. However, the injection locking occurs at four times of the reference signal, i.e. 4x6GHz=24GHz. The injection locked oscillator output is then either coupled to a millimeter wave spectrum analyzer to study of the injection locking process or as a 24GHz LO to a mixer for upconversion of the data signals.

The second group of FO links is for the purpose of the 0.5-1GHz data transmission to the active modules. This link consists of an optical transmitter, a fiberoptic power splitter, 50m of Siecor optical fiber, and two PIN photodiodes as the optical receiver. The optical transmitter was developed at Drexel using a SL300H BH laser diode from Ortel. This module is a self contained package with bi-directional temperature and optical power monitoring circuits. Furthermore, the transmitter module is raectively matched with the bias tee circuit over 0.5-1GHz band as opposed to the commercially available resistively matched modules. The laser diode has a threshold current of 16mA at room temperature with a 3dB bandwidth of 3GHz for I_b=43mA. The small-signal modulated laser optical

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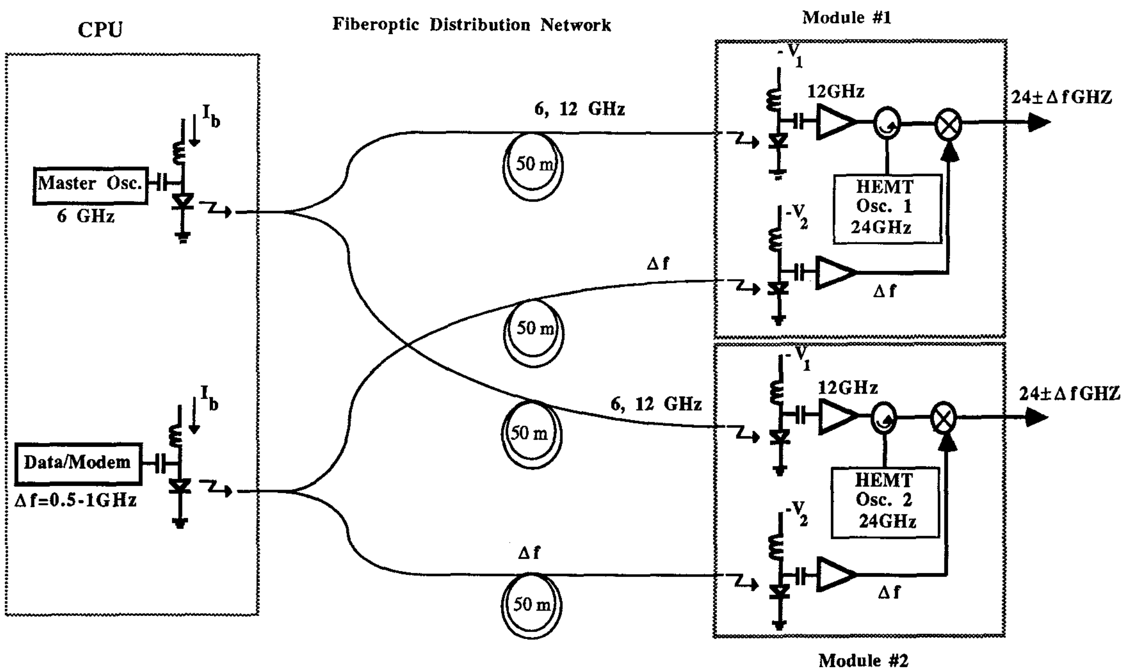


Fig. 1. Experimental setup for frequency synchronization of free running HEMT oscillators at 24GHz and 0.5-1GHz data transmission to active MMIC based T/R modules.

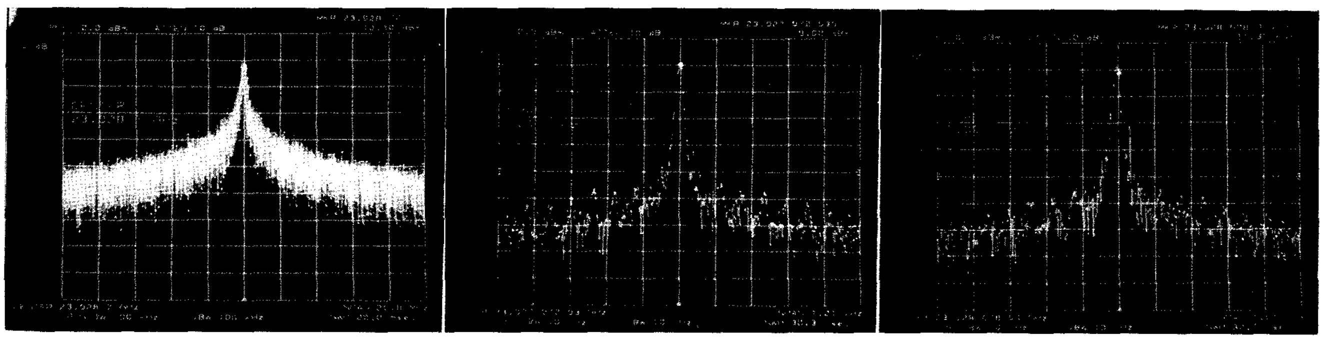
output is coupled to the 3 dB optical coupler and after transmission by 50m of fiber is detected by photodiodes. The demodulateded signal is inputted as the IF signal to a mixer from Avantek (DBX1824M) for upconversion by the stabilized LO. The upconverted signals are observed on the millimeter wave spectrum analyzer.

EXPERIMENTAL RESULTS

Performance of the synchronizing and data FO links were individually characterized. Then the overall performance of the commmunication network was evaluated.

Synchronization link

Spectrum of the free-running HEMT oscillator prior to injection locking is shown in Fig. 2a, where an output power of 10dBm at 23.928GHz is measured. The Q_{ex} of the oscillator was measured using electrical injection locking and was calculated to be 130. Since indirect fundamental optical injection locking of the oscillator at 24GHz can not be achieved, subharmonic injection locking at subharmonic factor of 1/2 was selected to stabilize the oscillator. In this experiment, harmonic generation in the laser and the transistor are both exploited, i.e. nf_0x2=23.928GHz where nf_0 is the nth harmonic of the modulating frequency f_0. The optical transmitter module was modulated by a 13dBm signal from a synthesized generator (HP8763C) at frequency of f_0. The large-signal modulation of laser generates harmonics which are detected by the high-speed photodiode and then amplified. More specifically, the harmonic of the master signal at 11.964GHz is amplified and is subharmonically injected to the oscillator. Fig. 2b and Fig. 2c depict power spectrum of the stabilized HEMT oscillator for master oscillator frequency of f_0=3.988049GHz (n=3) and



(a) (b) (c)

Fig. 2. Power spectra of the free-running and injection locked HEMT oscillator; a) free running (horizontal scale 2MHz/div); b) subharmonic optically injection locked at subharmonic factor of 1/6 (n=3) at f_0= 3.988049GHz (horizontal scale 100Hz/div); c) subharmonic optically injection locked at subharmonic factor of 1/4 (n=2) at f_0= 5.982159GHz (horizontal scale 100Hz/div). (Vertical scale of 10dB/div and center frequency of 23.928GHz).

Subharmonic Number (n)	Modulating Freq. f_0 (GHz)	Locking Range(MHz)	Phase noise offset carrier (dBc/Hz)		
			100 Hz	200 Hz	300 Hz
4	2.990304	8	-60	-65	-70
3	3.988049	14.4	-65	-68	-72
2	5.982159	14.4	-64	-67	-70
1	11.963972	1.1	-55	-63	-66

Table I. Comparison of the locking range and the FM noise level of the injection locked 24GHz HEMT oscillator at four different subharmonic numbers.

f_0=5.982159GHz (n=2) respectively, both indicating a drastic FM noise reduction. Results of subharmonic injection locking for n=1, 2, 3, 4 are summarized in Table I, where a locking range over 14MHz and FM noise level of -68dBc/Hz at 100Hz offset carrier for n=3 are attained. The FM noise for n=1 (f_0=11.964GHz) is the highest of all due to the small injected signal level rather than noise contributions from the laser diode at 11.964GHz. This deduction is made upon observing an increase in the FM noise level of the electrically injection locked oscillator as the injected power level was reduced. Study of the optically injection locked oscillators indicates that oscillator's output power varies over the locking range by 3dB, therefore limiting the usable locking range.

Data link

The optical transceiver was characterized in terms of linearity, gain, intermodulation distortion, and dynamic range over 500-1000MHz. Frequency response of data FO link demonstrated a flatness of ±3dB over this band. The input-output characteristics and linearity of the data link at laser biasing currents of 25mA and 30mA are shown in Fig. 3. A loss of ≈35dB was attained at 750MHz, which is primarily due to electrical mismatch of the Ortel PDO50 PIN photodiode ($|S_{22}|$≈0.4dB) and poor optical coupling to the fiber of 10%. Results of two tone third order intermodulation distortion measurement is also rendered in Fig. 3. A third order intecept points of +6dBm and +14dBm were calculated with corresponding 1dB compression points of -4dBm and +4dBm for the bias currents of 25 and 30mA respectively. To evaluate the dynamic range, the minimum detectable signal was calculated by measuring noise floor level due to the relative intensity noise (RIN) of laser diode. Dynamic range of 71dB/MHz for 25mA biasing current was calculated, whereas at bias current of 30mA dynamic range was measured to be 81dB/MHz.

Communication at 24GHz

To demonstrate communication at the carrier frequency of 24GHz, the SL300H BH laser diode was modulated by an FM signal at 750MHz with frequency deviation of 1kHz and modulation index of ß=1. Output of the data FO link is shown in Fig. 4a where the information is fully retrived. The detected signal was then upconverted by the optically synchronized LO at 23.927GHz without any amplification. Lower and upper side bands of the upconverted FM data are also shown in Figs. 4b and 4c. High conversion loss of 47dB is because of the LO input power of 0dBm versus the required 10dBm (a 10dB penalty from broadband coupler), 7dB conversion loss of mixer, and 12dB loss at 24GHz for the 2-18GHz bandwidth limit of DBX1824M mixer.

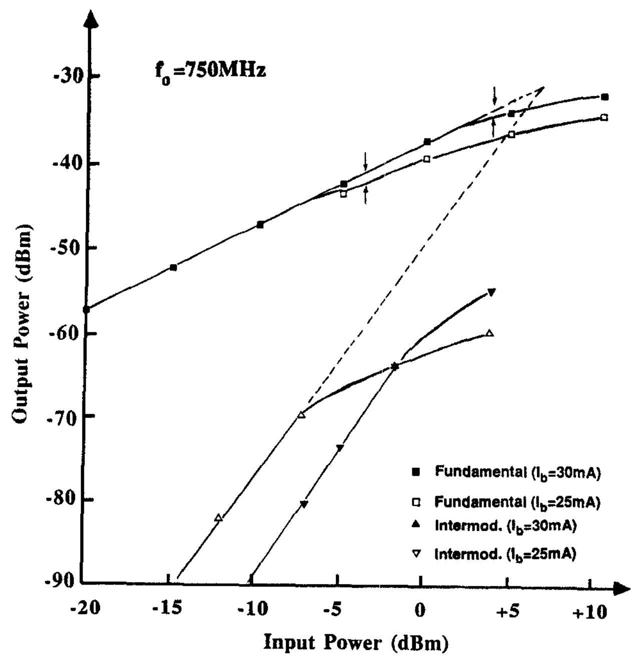
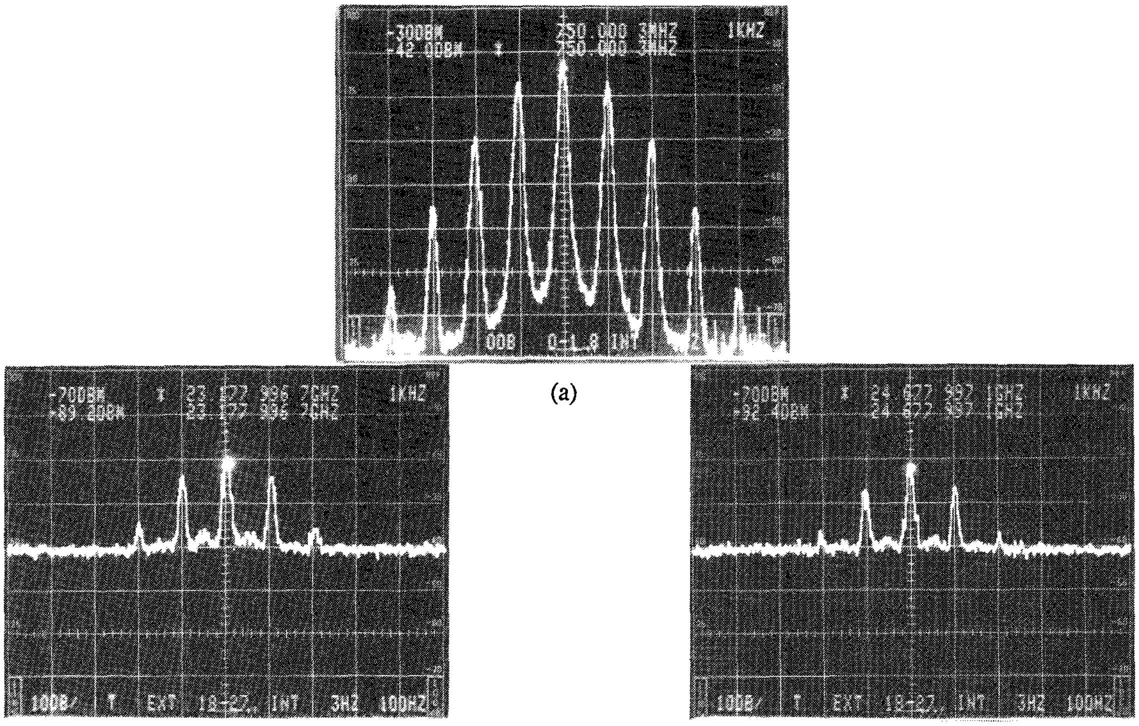


Fig. 3. Input and output power characteristics of the data FO link at 750MHz. Linearity and third order modulation distortion of the reactively matched optical transmitter module are also shown for two biasing currents of 25mA and 30mA. Arrows point to 1dB compression points for two different bias currents.



(a) (b) (c)

Fig. 4. Power spectra of the FM data at modulation index of ß=1; a) data after transmission through data FO link (center frequency of 750MHz and marker value of -42dBm); b) lower side band of data signal after upconversion by the stabilized 24GHz LO (center frequency of 23.177996GHz and marker value of -89dBm); c) upper side band of data signal after upconversion by the stabilized 24GHz LO (center frequency of 24.677997GHz and marker value of -92dBm). (Vertical scale of 10dB/div and horizontal scale of 1kHz/div.)

DISCUSSION

Since fiber-optic links in the future large phased array antennas perform multifunction tasks, the system requirements of these links are different. This paper has presented experimental results of fiberoptic communication at carrier frequency of 24GHz with FM bandwidth of 0.5-1GHz on the basis of *T/R level data mixing*. This approach could extend operating bandwidth of directly modulated FO links to millimeter wave frequency range, and surpass the 10GHz limit. Furthermore, this approach resulted in a 22dB dynamic range improvement over the alternative approach, viz. *CPU level data mixing* (5). Indirect optical injection locking of HEMT oscillator at 24GHz with a modest locking range of 14MHz using commercial FO links was demonstrated. However, comparison between the present experiment and the previously reported results (6) confirms the need for judicious selection of optical modulation depth and the modulating frequency to enhance the locking range and reduce FM noise degradation. The data FO link was characterized over 500-1000MHz in terms of gain-bandwidth and dynamic range. Comparison between results of the reactively matched transmitter module developed at Drexel versus the commercial modules with resistive matched circuits point out to three subtle issues. First, since gain of FO links is directly related to the ratio of photodiode output resistance over laser diode input resistance (5), loss can be minimized by taking advantage of reactively matched optical transmitter and receiver modules whinch this ratio is much larger than unity. Second, at least a 10dB improvement in sensitivity and noise figure of reactively matched FO links is anticipated, which is primarily due to 10dB reduction in the laser diode's noise power. Third, with appropriate selection of biasing current the third order intercept can be improved.

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