High-Speed Fiber-Optic Links for Distribution of Satellite Traffic

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Abstract —**Large-aperture phased array antennas operating at millimeter-wave frequencies are designed for space-based communications and imaging platforms. Array elements are comprised of active T/R modules which are linked to the central processing unit through high-speed fiber-optic networks. The system architecture that best satisfies system requirements at millimeter-wave frequencies is *T/R level data mixing*, in which data frequency and reference signals are distributed independently before mixing at the T/R modules. This paper demonstrates the design procedures for a low-loss, high-speed fiber-optic link used for transmission of data signals over a 500–1000 MHz bandwidth as part of a data link in the T/R level mixing architecture. The FO link is characterized for transmission of analog and digital data. A dynamic range of 88 dB/MHz was measured for analog data over this bandwidth. On the other hand, for bursted SMSK satellite traffic at 200 Mb/s rates, a BER of 10^{-9} was measured for E_b/N_0 of 15.5 dB.**

I. INTRODUCTION

LARGE-APERTURE phased array antennas composed of many monolithic microwave integrated circuit (MMIC) based transmit/receive (T/R) modules will play an increasingly important role in future communication and imaging systems. These antennas offer the flexibility necessary for airborne and space-based platforms to handle the demand for rapid beam-hopped variable area coverage communication links. For example, in new generations of communication satellites, at least 10^2 to 10^3 active phased array antennas operating at *Ka*-band are used as feeds for a reflector antenna. Conventional precision waveguide feed networks, used to distribute control and communication signals from an on-board processor to the large number of distributed T/R modules that form the active aperture, are bulky and complicated. A fiber-optic network is therefore selected as a replacement. The significant advantages of optical fibers over coaxial, precision waveguides and space-fed configurations are many and thus fiber-optic (FO) distribution networks are considered a viable approach [1]. Among many signals transferred through FO links between the active aperture and the on-board processor, data and frequency reference links have the most stringent requirements. The challenge is to design FO links up to millimeter-wave frequencies satisfying bandwidth, linearity, low-noise-figure, and high-dynamic-range requirements. Unfortunately all specifications cannot simultaneously be met in an FO link; the approach pursued is that rather than distributing the modulated carrier using one FO link, carrier and data signals are separately distributed and after detection at each subarray, they are mixed at the T/R module to construct the modulated carrier.[1] This scheme is more advantageous since the carrier FO link can be optimized for bandwidth requirements while the data link is operated at a lower frequency for a linear and low-noise performance. This approach is called *T/R level data mixing*, as opposed to the former technique, which is called *CPU level data mixing*. Using this approach coherent communication up to 40 GHz has been demonstrated [2]. The technique most suited for providing the same millimeter-wave carrier signal to all active modules is indirect subharmonic optical injection locking of free-running oscillators by distributing a frequency reference from a master oscillator. The nonlinear characteristics of both laser diode and slave oscillator can be exploited to extend the synchronizing frequency to *Ka*-band [3], [4].

It should be noted that by separating the data and frequency reference FO links, each link can be optimized; and since performance of the data FO link is of great concern, attention is directed to the performance of this link. The goal of this paper is to present the design of optical transmitter and receiver modules for establishing a high-performance data FO link. The design criteria of low loss, low noise, and high dynamic range are set for modules such that the required specifications for FO links would be met. The FO link performances for both analog and digital data over the bandwidths necessary for satellite traffic are also presented.

Manuscript received August 20, 1989; revised November 13, 1989. This work was supported in part by the NASA Lewis Research Center, the GE Astro-Space Division, and Dupont under the Advanced Technological Center for the State of Pennsylvania's Ben Franklin Partnership Program.

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IEEE Log Number 9034821.

[1] Cf. the accompanying paper in this issue by A. S. Daryoush (pp. 467–476).

II. DESIGN OF LOW-LOSS FIBER-OPTIC LINK

In order to fully realize the advantages of a directly modulated intensity detection FO link, as applied to any distributed communications network, every attempt must be made to minimize losses of signal power throughout the link. This is a complex problem, as can be seen from the equation for the link's total gain G:

$$G = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1}{4}(\eta_L K_L L K_D \eta_D)^2 |H_L(I_b,f)|^2 |H_D(V_r,f)|^2 \cdot \frac{(1-|S_{11}|^2)(1-|S_{22}|^2)}{\operatorname{Re} Z_L \times \operatorname{Re} Y_D}.$$

For a typical FO link in practice we are dealing with a high insertion loss of order 30 to 40 dB rather than gain. The purpose of the following analysis is to identify a method to minimize FO link loss.

Based on the selected components and operating wavelength, clearly some insertion loss contributions to the overall gain are totally unavoidable; these loss terms are primarily in the optical domain due to the laser and detector coupling and quantum inefficiencies ($\eta_L K_L$ and $\eta_D K_D$), the optical fiber and connector/splice losses (L), and the frequency response of the laser and detector (H_L, H_D). Since in a well-designed short-haul FO link, the laser and detector are selected such that their rise and fall times are faster than the data rate and the fiber loss is insignificant, the predominant insertion loss of FO links is contributed by $(\eta_L K_L \eta_D K_D)^2$, which is typically in the range of -20 to -30 dB. In addition, reflected power at the input of the laser diode $(1-|S_{11}|^2)$ and at the output of the detector $(1-|S_{22}|^2)$ introduces an additional loss of 10 to 30 dB to the overall loss. However, the return loss contribution can be minimized by designing optical transmitter and receiver modules that are matched to a standard 50 Ω system. Furthermore, by taking advantage of reactive matching, the inherent low impedance of the laser diode and high impedance of the detector will lead to a transducer gain of $\{\operatorname{Re}(Y_D)\operatorname{Re}(Z_L)\}^{-1}$. Therefore, lower loss FO links can be realized using reactively matched optical transmitter and receiver modules as have been pursued by other researchers recently [5], [6]. The factor 1/4 is because one half of the photodetected current passes through the conductance of the current source for the reactively matched p-i-n photodiode. However, there is a distinct trade-off between the minimum acceptable return loss to be realized and the bandwidth over which impedance matching is to be performed. This compromise is expressed by Fano's equation [7]:

$$|\Gamma|_{\min}(\text{in dB}) = -\frac{27.3 f_0}{\Delta f Q}$$

where f_0 is the frequency at band center and Q is the quality factor of the device to be matched to a 50 Ω system. The minimum achievable return loss therefore depends on the data bandwidth (Δf) and the half-power bandwidth (f_0/Q) of the device.

The next important factor in the performance of high-speed analog FO links is dynamic range. Throughout this paper we have used compression dynamic range (CDR), which is limited at the upper end by the 1 dB compression point of the laser diode and at the lower end by the noise floor of the FO link. Since the laser diode nonlinearity is dependent on the current modulation index [8], small-signal operation is recommended. Furthermore, the laser nonlinearity for the given modulation index is peaked at frequencies close to the large-signal relaxation oscillation frequency [8]; hence by biasing the laser diode close to the maximum output power not only can the relaxation oscillation frequency be shifted outside the data bandwidth, but also for the given RF input power a lower current modulation index is achieved, leading to lower two-tone intermodulation distortion.

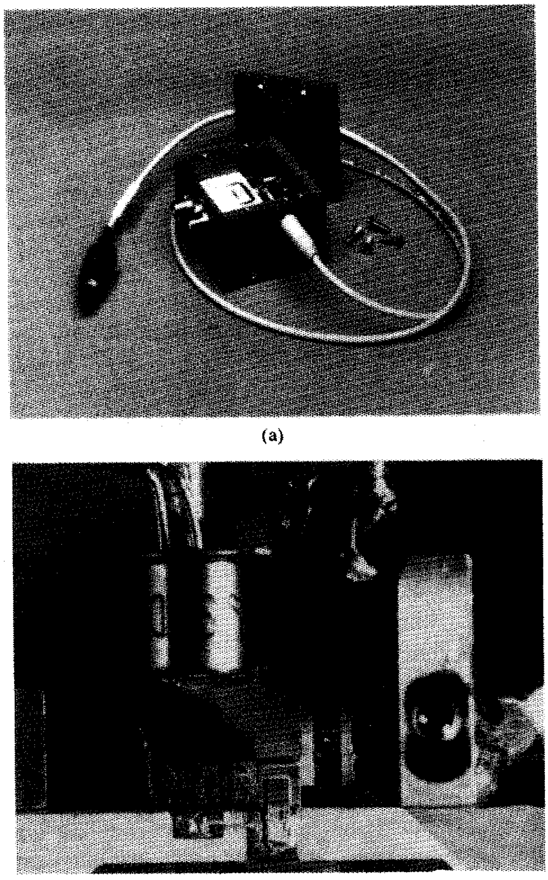
The noise floor of FO links, on the other hand, is directly proportional to the link noise figure, basically expressed as

$$\mathrm{NF} = \frac{(I_b - I_{\text{th}})^2 \operatorname{Re} Z_L \times \mathrm{RIN}(I_b,f)}{k_B T} + \frac{2e(I_b - I_{\text{th}})}{k_B T\sqrt{G}} \sqrt{\frac{\operatorname{Re} Z_L}{\operatorname{Re} Y_D}}.$$

The first term is the thermal noise contribution from the optical transmitter (laser diode) whereas the second term is the shot noise contribution from the optical receiver (photodiode). For a reactively matched laser diode, the overall noise contribution from the input is reduced since the input resistance (i.e., $\operatorname{Re}\{Z_L\}$) of a forward-biased p-n junction is very small. In addition, the FO noise figure for short-haul FO links is dominated by the laser noise, signified by the relative intensity of the laser (RIN). Laser noise is peaked at the relaxation oscillation frequency and is greatly influenced by any light feedback into the active region of the laser diode. The magnitude of RIN is largely dependent on the length of the Fabry–Perot cavity [9]. Therefore, by coating the back facet of laser diodes with reflective material, because of the double pass of photons through the Fabry–Perot cavity, a lower RIN is anticipated.

III. DESIGN OF OPTICAL TRANSMITTER MODULE

The first step in the design of an optical transmitter satisfying an analog data transmission bandwidth of 500–1000 MHz is device selection. An AlGaAs laser diode from Ortel Corporation (SL300H) operating at 820 nm was selected as the source due to its compatibility with GaAs MMIC processing. This will permit eventual integration of electro-optical components with electronic circuits. The 3 dB bandwidth of the laser diode is 3 GHz for bias current of 35 mA; the laser diode has front and back facet reflectivities of 0.3 and 0.7 respectively to reduce the strength of the relaxation oscillation frequency



(a)

(b)

Fig. 1. Final implementation of the reactively matched optical transmitter module designed for operation at 750±250 MHz. (a) Overall view with 4-40 screws for size comparison. (b) Close-up view of the laser diode's TE cooler, monitor detector, and fiber coupling.

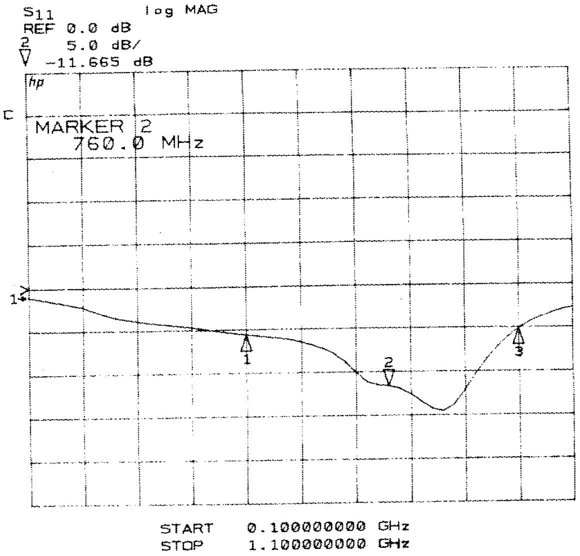


Fig. 2. Return loss of the optical transmitter as a function of frequency.

and hence its RIN [10]. To design a reactive impedance matching network, the laser diode impedance should be de-embedded out of the test fixture's total scattering parameter [11], then converted to an equivalent circuit model to calculate the minimum attainable reflection coefficient using Fano's equation. For the de-embedded impedance of the laser diode, a theoretical limit of $|\Gamma_{\min}| = -34$ dB was calculated. Since the selected space for the impedance matching and bias tee networks on the RT/Duroid substrate of $\epsilon_r = 10.5$ is 1 in × 1.5 in, a combination of distributed and lumped elements is used to obtain a low return loss of ~ -10 dB over the 0.5 to 1 GHz frequency range.

The impedance matching iterations were initiated using various circuit topologies on the Touchstone CAD program, and the one comprising a distributed inductor and shunt lumped and distributed capacitors, as shown in Fig. 1, was selected. The return loss performance of the reactively matched optical transmitter is shown in Fig. 2, where satisfactory matching of $|S_{11}|^2 \leqslant -7$ dB is accomplished over 600–900 MHz. Details of the components required to control the performance of the optical transmitter module are shown in Fig. 1(a), where the thermistor and TE cooler, as well as the optical prism and monitor detector, can be clearly seen. The monitor photodetector is incorporated to adjust the bias current of the laser by monitoring the back-facet light output power of the laser, and the bidirectional TE cooler is capable of cooling from $-10°$ to $+60°$C. The close-up view of the light coupling to a multimode (50/125 μm) fiber is shown in the same figure, where an optical coupling loss of $K_L = -5$ dB is measured using a simple butt coupling technique.

The performance of the optical transmitter using a commercial high-speed photodiode (Ortel PDO-50) is shown in Fig. 3, where an insertion loss of roughly 34 dB for laser bias current of 25 mA is measured. This performance is better than the loss of commercial links by as much as 10 dB.

IV. Design of Optical Receiver Module

The design of the optical receiver module follows the same procedure as the optical transmitter. A wavelength matching AlGaAs p-i-n photodiode from Ortel Corporation (PDO50-C) was selected, which has 3 dB bandwidth in excess of 6 GHz. The maximum detector responsivity is 0.45 mA/mW at 850 nm. The impedance of the detector was also de-embedded out of the measured test assembly S parameters and was found to be essentially a capacitor (~ 2.5 pF) in shunt with a very large resistance (~ 5 kΩ), as expected for a reverse-biased p-n junction. This yields a Q of about 60 at $f_0 = 750$ MHz. Fano's equation therefore dictates that the best return loss that reactive matching can accomplish over the 0.5 to 1.0 GHz band is only -0.5 dB. This result indicates that due to the high Q

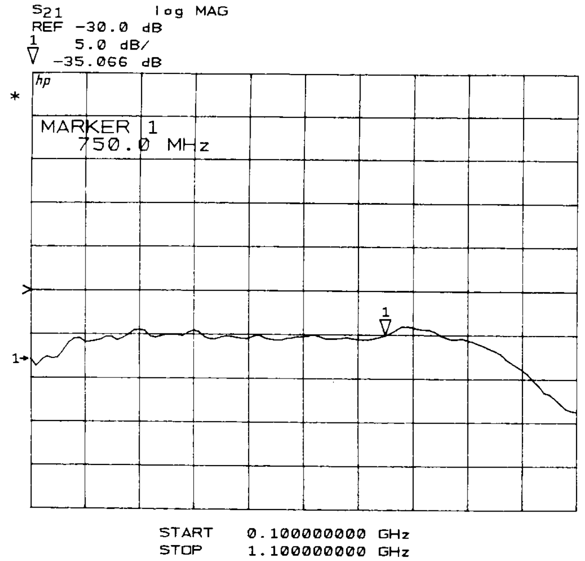


Fig. 3. Measured insertion loss of the transmitter module using a commercial optical receiver as a function of frequency. The laser diode bias current is 25 mA. (Start frequency of 100 MHz and stop frequency of 1100 MHz, reference level of −30 dB, and vertical scale of 5 dB/div, and Marker 1 value of −35 dB.)

factor of the p-i-n photodiode, reactive impedance matching of the detector to 50 Ω is impossible. Indeed, most commercially available receivers do not include any such reactive network and therefore experience a large return loss.

If the 500 MHz bandwidth requirement were relaxed, it is predicted that a satisfactory return loss of $|S_{22}|^2 \leqslant -10$ dB could be obtained over a narrow band of 20 MHz centered at 750 MHz. A receiver module can now be designed to verify the predicted transducer gain out of the reactively matched optical transmitter and receiver modules. Due to the small bandwidth requirement, 20 MHz, the matching filter is of very low order and can be realized using distributed components. A simple design topology employed is a lumped-element inductor in series with the photodiode followed by a single quarter-wave transformer for narrow-band matching at 750 MHz. Analysis with Touchstone CAD predicted that this design would yield $|S_{22}|^2 \leqslant -28$ dB over a frequency range of 750 ± 10 MHz, but would be highly sensitive to the inductance of the lumped element and to any parasitics associated with the chip inductor, the photodiode, and bond wires. To verify the FO link gain expression, an optical receiver was designed and fabricated; a return loss of −22 dB was measured at 740 MHz. A FO link was then established using the designed optical transmitter and receiver modules, resulting in a total insertion loss of −28 dB at 740 MHz. Table I summarizes the loss associated with each term contributing to the overall FO insertion loss. The experimental result verifies the analytical prediction; thus design of a broad-band matching network was pursued for the receiver module. Note that laser and photodetector coupling efficiencies can be improved, thereby reducing the insertion loss by at least 10 dB. Further improvement in the design of a low-parasitic-loss reactive matched network will increase transducer gain.[2]

TABLE I
FO LINK INSERTION LOSS BREAKDOWN OF THE REACTIVELY MATCHED OPTICAL TRANSMITTER WITH A NARROW-BAND REACTIVELY MATCHED OPTICAL RECEIVER AT 750 MHz

<table>
<tr><th></th><th colspan="5"></th><th>Gain</th></tr>
<tr><td rowspan="2">Optical Losses</td><td>$\eta_L^2 = \left(0.4 \frac{mW}{mA}\right)^2$</td><td>$K_L^2$</td><td>$L^2$</td><td>$K_D^2$</td><td>$\eta_D^2 = \left(0.45 \frac{mA}{mW}\right)^2$</td><td rowspan="2">-31.5 dB</td></tr>
<tr><td>$-8\ dB\left(\frac{mW}{mA}\right)^2$</td><td>−9.5 dB</td><td>-2 dB</td><td>-5 dB</td><td>$-7\ dB\left(\frac{mA}{mW}\right)^2$</td></tr>
<tr><td rowspan="2">Transducer Freq. Response</td><td colspan="2">$|H_L|^2 \, |H_D|^2 \cong 1$</td><td colspan="2">$(1-|S_{22}|^2)$</td><td>$(1-|S_{11}|^2)$</td><td rowspan="2">- 1 dB</td></tr>
<tr><td colspan="2">0 dB</td><td colspan="2">− 0.5 dB</td><td>−0.5 dB</td></tr>
<tr><td rowspan="2">Transducer Gain</td><td colspan="2">$[\mathrm{Re}(Z_L) \approx 22.5\ \Omega]^{-1}$</td><td colspan="2">$\frac{1}{4}$</td><td>$[\mathrm{Re}\{Y_D\} \cong 5\ mS]^{-1}$</td><td rowspan="2">3.5 dB</td></tr>
<tr><td colspan="2">- 13.5 dBS</td><td colspan="2">−6 dB</td><td>+ 23 dBΩ</td></tr>
<tr><td></td><td colspan="5"></td><td>- 29 dB</td></tr>
</table>

Broad-Band Receiver Design

Implementation of a reactively matched receiver module demands two important compromises: i) lowering the device Q and ii) reducing bandwidth. Lowering the Q of the capacitive photodiode is achieved first by introducing a series inductance such that the effective capacitance of the diode is reduced and second by adding a series resistor of 15 Ω to the detector. Even though the series resistor will reduce the Q of the device, the penalty is a reduction of the transducer gain (i.e., $\{\mathrm{Re}(Y_D)\mathrm{Re}(Z_L)\}^{-1}$). Nevertheless reducing the data bandwidth to 600–900 MHz results in a limited information bandwidth. For example, for the serial-minimum-shift-keyed (SMSK) digital format, the maximum allowable data rate to pass through such a link will be 200 Mb/s. However, a theoretical minimum return loss limit of − 13 dB is calculated.

This approach was pursued and the receiver module containing a multistage lumped matching network was designed, as shown in Fig. 4. The optical receiver module comprises fiber optical coupling to the p-i-n photodiode and a *pseudoreactive* matching network. Optimum light coupling from the multimode fiber to the active region of the photodiode (50 μm in diameter) is ensured by a focusing technique using a 0.29 pitch cylindrical graded index (GRIN) lens. Using this focusing system, a light coupling of $K_D = -3.5$ dB was measured. The return loss of the optical receiver is shown in Fig. 5, which at worst is −2.5 dB, corresponding to the band edge of 900 MHz. The insertion loss of the FO link using the optical transmitter and this receiver module for various laser bias

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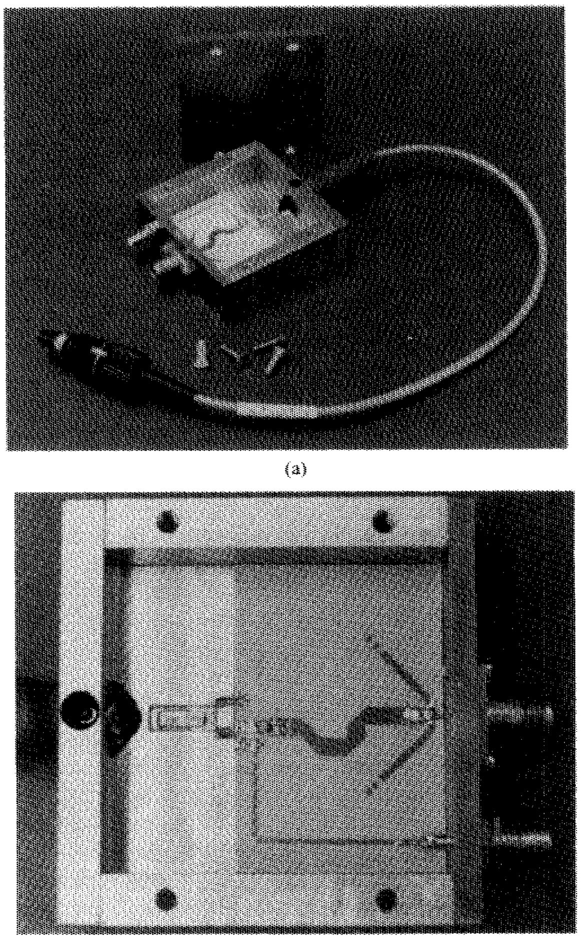
[2] Recently, by optimizing the electrical and optical characteristics of the optical transmitter and receiver over narrow-band frequency at 900 MHz, a gain of +3 dB was measured [12].



(a)

(b)

Fig. 4. Overall view of an optical receiver module with pseudoreactive matching network. (a) Overall view with 4–40 screws for size comparison. (b) Close-up view of the 0.29 pitch GRIN lens, ceramic submount for mounting of the p-i-n photodiode, and pseudoreactive matching circuit.

levels is depicted in Fig. 6, where a 30 dB loss is attained over the band.

V. FO LINK PERFORMANCE

A FO link consisting of the optical transmitter, 50 m of multimode (50/125 μm) optical fiber from Siecor, and the broad-band optical receiver module was established, and its performance was characterized in terms of analog and digital data signals.

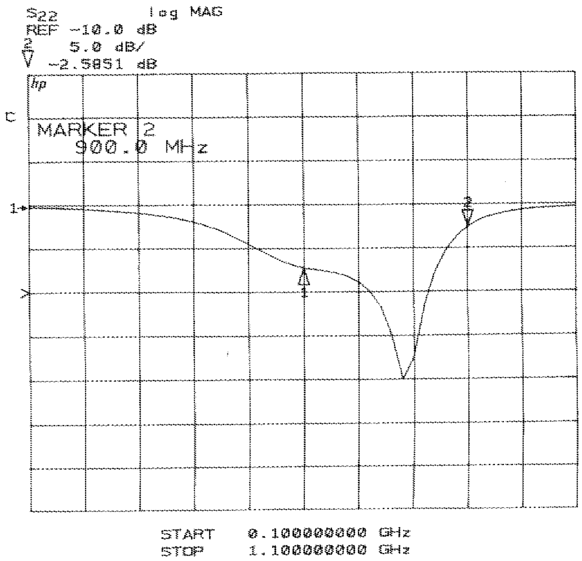


Fig. 5. Return loss of the broad-band pseudoreactively matched optical receiver as a function of frequency. Markers indicate a 600–900 MHz band. (Vertical scale is 5 dB/div., horizontal scale of 100 MHz/div., and reference level at −10 dB.)

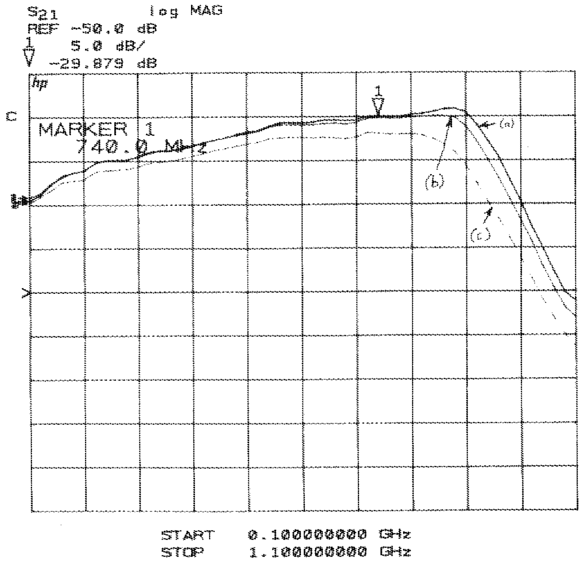


Fig. 6. Insertion loss of the 600–900 MHz FO link as a function of frequency. Laser bias levels of (a) 20 mA, (b) 25 mA, (c) 30 mA. (Vertical scale of 5 dB/div., horizontal scale of 100 MHz/div., and reference level of −50 dB.)

A. Analog Data

The FO link was characterized in terms of linearity, gain, intermodulation distortion, and dynamic range over 600–900 MHz. The frequency response of the data FO link demonstrated a flatness of ±1.5 dB over this band. The input–output characteristics and linearity of the link at a carrier frequency of 750 MHz for laser biasing currents of 25 and 30 mA are shown in Fig. 7. Similar results were also measured over the 500–1000 MHz band. An insertion loss of ~30 dB was attained at 750 MHz, which, as discussed earlier, is primarily due to pseudoreactive matching at the optical receiver and poor optical coupling efficiency. Even though this result is better than any other reported results, it can still be improved upon [12]. Results of a two-tone third-order intermodulation distortion measurement at 750 MHz are also rendered in

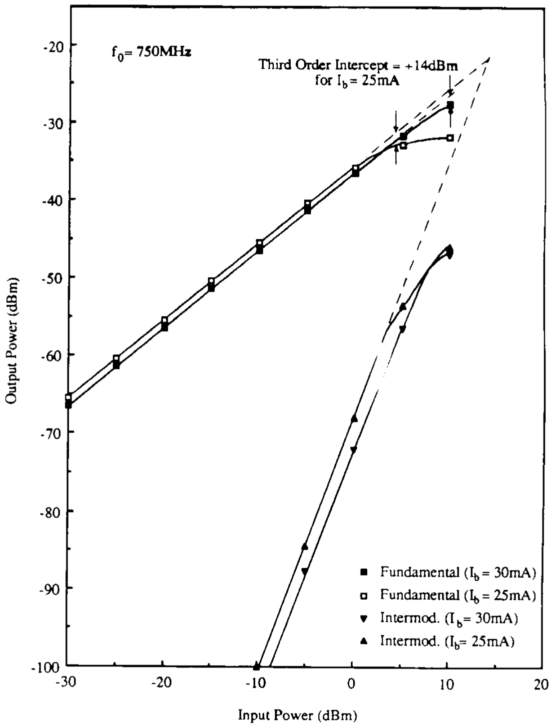


Fig. 7. Input and output power characteristics of the data FO link at 750 MHz. The linearity and third-order modulation distortion of the reactively matched optical transmitter module are also shown for two biasing currents of 25 and 30 mA. Arrows point to 1 dB compression points for the two different bias currents.

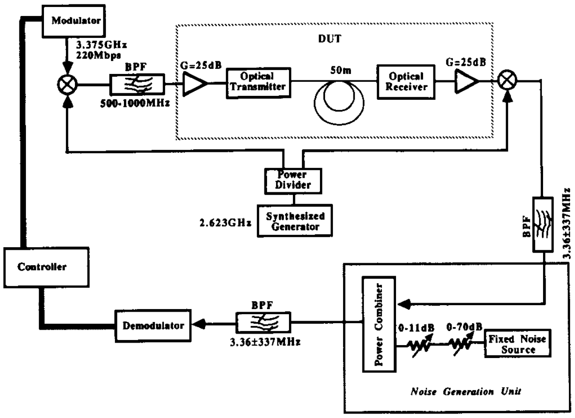


Fig. 8. Experimental setup for measurement of the bit error rate of a 600–900 MHz FO link using 200 Mb/s bursted pseudorandom data from a SMSK modulator at 3.37 GHz.

Fig. 7. Third-order intercept points of +14 and +20 dBm were calculated with corresponding 1 dB compression points of +4 and +10 dBm for the bias currents of 25 and 30 mA respectively. Similar performance was measured at other frequencies in the band.

To evaluate the dynamic range, the minimum detectable signal was calculated by measuring the noise figure of the 50 m FO link which is dominated by the relative intensity noise (RIN) of the laser diode. Since the laser diode has a back facet reflective coating (asymmetric structure), the RIN is lower than for symmetric structures; in addition the total noise power is lower because of reactive matching in the optical transmitter. The combination of these two factors has resulted in an NF of 35 dB and hence a noise floor level of −78 dBm for a laser diode biasing current of 30 mA. This corresponds to a compression dynamic range of 88 dB/MHz at 750 MHz, which is much higher than any other reported result.

B. Digital Data

To characterize the FO link performance in terms of digital satellite traffic, a bit error rate test set was used. The experimental arrangement shown in Fig. 8 provides a bursted 221 Mb/s pseudorandom data stream to FO links at a carrier frequency of 750 MHz. The modulator outputs a −10 dBm SMSK signal at a 90% burst rate and a carrier frequency of 3.37 GHz. This results in an actual data throughput of 200 Mb/s. This signal is down-converted by a synthesized generator to 750 MHz, which is filtered by a 750±250 MHz coaxial filter. This signal is amplified to +6 dBm and is then used to modulate the optical transmitter. The output of the laser is coupled to the broad-band optical receiver either through a short length of the multimode optical fiber or through the 50 m of multimode fiber from Siecor. The demodulated digital signal is then amplified and is up-converted by the same synthesized generator to 3.373 GHz. The output of the mixer at the RF port is filtered by a 337 MHz wide filter and is fed into a noise generator box. The input power to the noise generator box is kept at a fixed level of −11 dBm for all measurements. A calibrated noise power is then added to the injected signal and is controlled using controllable attenuators such that a constant input power of −33 dBm is fed into the demodulator box. By direct comparison of each single bit transmitted to the bit received, the bit error rate is calculated and is displayed by the controller. The modulated signal and noise powers recorded during calibration of the noise generation unit were used to determine two similar parameters—energy per bit (E_b) and noise power spectral density (N_0). These values are based on the system data rate and are calculated using the expression

$$E_b/N_0\,(\mathrm{dB}) = (P_s - P_n) - D + N_{\mathrm{bw}} - R$$

where

P_s	measured signal power, dBm
P_n	measured noise power, dBm
D	duty cycle of bursted data = 90.4% = −0.437 dB
N_{bw}	noise bandwidth of calibration filter = 379.69 MHz = 85.79 dBHz
R	data rate = 221.184 Mb/s = 83.45 dBHz.

The noise added by the noise generator is assumed to be additive white Gaussian, which allows us to define the

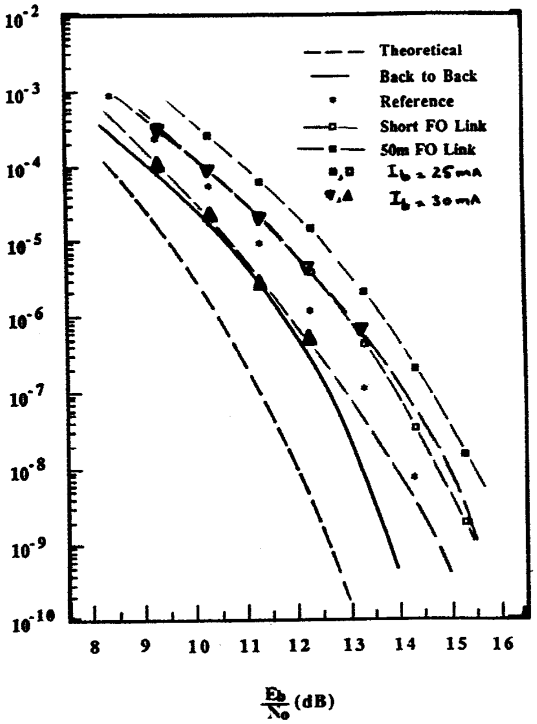


Fig. 9. BER characterization of the FO link as a function of E_b/N_0 for laser diode bias currents of 25 and 30 mA. (A short length of optical fiber is presented in red whereas a 50 m length of multimode fiber is in green). The pseudorandom digital signal is bursted SMSK of 200 Mb/s rate. Baseline characteristics of theoretical, back-to-back, and reference results are also presented in relation to the FO link performance.

theoretical probability of error for the electronic circuitry as

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{E_b}{N_0}\right)^{1/2}$$

where the complementary error function is defined as

$$\mathrm{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt.$$

The measurements were conducted as follows. First the system was calibrated by measuring a direct connection of the modulator to the demodulator. This back-to-back measurement along with the theoretical expectation is shown in Fig. 9, indicating the integrity of the electronic system. In the same graph is the BER measurement of the reference system, established by placing a 30 dB attenuator in place of the FO link in the experimental setup. Finally, a direct BER measurement of the FO link was conducted for a laser diode bias level of 25 mA. Two separate measurements of: i) the short FO link and ii) the same link with 50 m of optical fiber were conducted and the results of these measurements are also rendered in Fig. 9. For example, a bit error rate of 2×10^{-7} was measured for $E_b/N_0 = 14.3$ dB for 50 m of optical fiber, whereas for the short optical fiber a 3×10^{-8} error rate was measured for the given E_b/N_0. Furthermore, by biasing the laser diode at 30 mA, an order-of-magnitude improvement in the bit error rate was observed. That is, a bit error rate of 5×10^{-7} was measured at $E_b/N_0 = 13.3$ dB for 50 m of optical fiber, and this result can be extrapolated to predict a BER of 10^{-9} at $E_b/N_0 = 15.5$ dB. In terms of the detected optical power an E_b/N_0 ratio of 15.5 dB corresponds to only -25 dBm of optical power that must be incident upon the detector in order to ensure a BER of 10^{-9}. These results also indicate that the power penalty for the 50 m of optical fiber versus the short optical fiber is only 1 dB.

VI. CONCLUSIONS

Low-loss fiber-optic links are designed for distribution of data and the frequency reference in large-aperture phased array antennas based on the T/R level data mixing architecture. In particular, this paper presented design aspects of a fiber-optic link satisfying the distribution requirements of satellite data traffic. The design was addressed in terms of reactively matched optical transmitter and receiver modules. Analog and digital characterization of a 50 m fiber-optic link realized using these modules has indicated the applicability of this architecture as the only viable alternative for distribution of data signals inside a satellite at present. Furthermore, this paper has demonstrated that the design of reactive matching networks for the optical transmitter and receiver modules enhances the link performance. Specifically, the dynamic range of 88 dB/MHz reported for this link is better than any previously reported analog link performance. Additionally, the E_b/N_0 of 15.5 dB is sufficient to meet the 10^{-9} BER link requirement.

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