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Bit-Error-Rate Testing of Fiber Optic Data Links for MMIC-Based Phased Array Antennas

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BIT-ERROR-RATE TESTING OF FIBER OPTIC DATA LINKS FOR MMIC-BASED PHASED ARRAY ANTENNAS

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Introduction

As satellite communications systems continue to evolve and grow in complexity, the associated antenna systems must also develop new features and capabilities. Such developments in antenna function have been shown to be achievable through the integration of monolithic microwave integrated circuits (MMIC's) and phased array antennas. Phased array antennas themselves offer many advantages over conventional antenna designs, including rapid, variable area coverage and electronic beam steering. Unfortunately, the increased number of radiating elements creates tremendous packaging and integration problems, thereby threatening the success of these desired communication systems.

High-frequency, densely packed microwave phased arrays for space applications require beam forming networks (BFN's) that are physically small and light, mechanically flexible, and low in loss. Toward this end, recent research in fiber optics indicates that optical fiber BFN's may offer an alternative to the larger, more awkward methods currently in use (ref. 1). As part of its research on using optics in antennas, NASA sponsors a cooperative agreement with Drexel University to investigate high-frequency optical radiofrequency (RF) links. Specifically, the objective of this work is to design, fabricate, and demonstrate an 18-GHz optical RF link by using an injection-locked RF fiber optic link technique developed at Drexel University.

As the fiber optic components are developed, they are subjected to an extensive series of verification tests. One such test assesses the ability of the fiber optic link to carry modulated, digital data such as that used in actual satellite communication systems. This paper describes the measured performance of a fiber optic data link that was subjected to bursted, serial-minimum-shift-keyed (SMSK) digital data at the NASA Lewis Research Center. Test procedures, experimental arrangements, and test results are presented.

Fiber Optic Data Link Operation

The fiber optic link discussed in this paper is one of two fiber optic links that together make up the injection-locked RF fiber optic link (IRFFOL). The IRFFOL technique is intended to permit the transmission and distribution of RF information from a central processing unit to remote MMIC modules located in the aperture plane of a phased array antenna. One fiber link, referred to as the fiber optic data link (FODL), carries the communications information and thus requires adequate bandwidth and a good overall signal-to-noise ratio.

The second fiber optic link, referred to as the fiber optic reference link (FORL), is a high-frequency, narrow-band link that transmits a reference RF signal to each remote MMIC module in order to phaselock a free-running field effect transistor (FET) oscillator. The final component of the IRFFOL system is a mixer that upconverts the FODL communications data to the MMIC RF carrier frequency. Figure 1 is a block diagram of the components used in the IRFFOL.

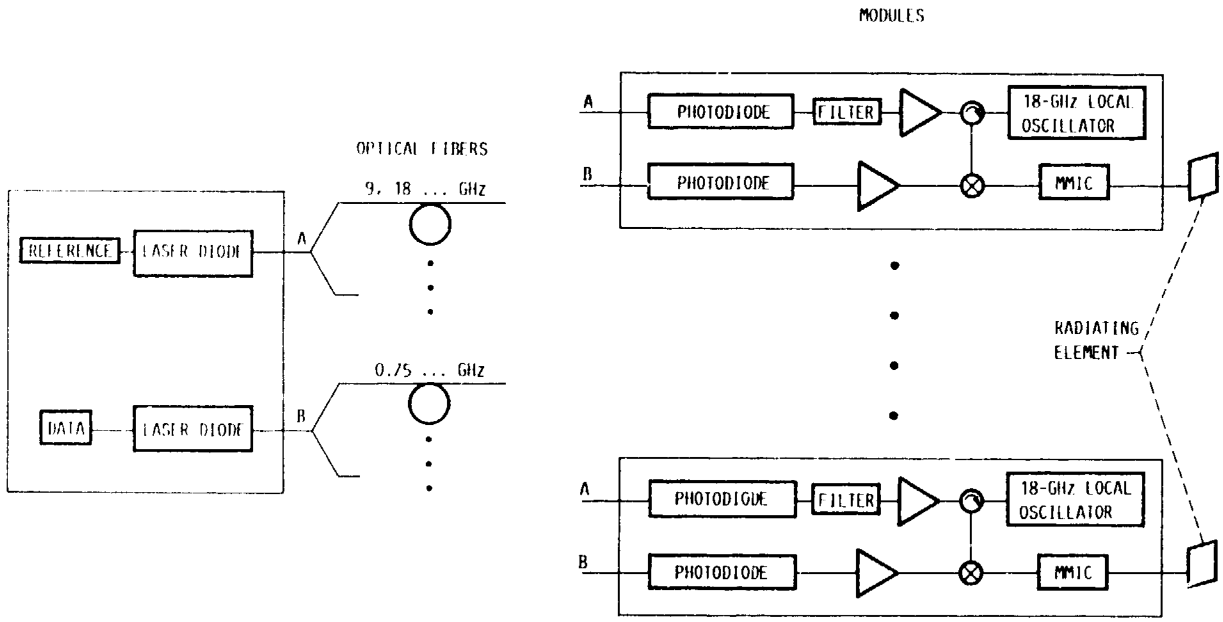

FIGURE 1. - INJECTION-LOCKED RF FIBER OPTIC LINK BFN DESIGN.

Because the FODL operates at lower frequency, it uses laser diodes and photodiodes that are operational at 820 nm and from 0 to 3 Ghz. The laser diode is biased in the 20 to 30 mA range, and the detector photodiode current is from 120 to 300 μA. Since the laser is operated far from the relaxation oscillation frequency, the output frequency spectrum is substantially free of harmonic content. However, severe mismatch problems occur because the laser input impedance is characteristically very low and the detector input impedance is characteristically very high, and both of them are poorly matched to the 50-Ω RF transmission lines. To aid in creating better impedance matches, reactive matching networks were built. But even reactive matching is not a complete solution because a tradeoff among return loss, insertion loss, and bandwidth has to be made. Figures 2 and 3 show the optical transmitter and receiver test units.

FIGURE 2. - OPTICAL TRANSMITTER.

FIGURE 3. - OPTICAL RECEIVER.

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The FORL is operated at a higher frequency, but in a much narrower bandwidth. The purpose of this link is to supply a reference signal that will phaselock the oscillation of a remotely located, free-running FET oscillator. At this time, semiconductor laser diodes are limited in directly modulated frequencies of operation to below 15 GHz for modest bias currents. At frequencies in excess of 15 GHz, RF optic links can be used for RF carriers by taking advantage of the inherent nonlinearity of laser diodes. Large-signal modulation of the laser diode for the frequencies in the proximity of the large-signal relaxation oscillation frequency results in a distorted light output with a high harmonic content (ref. 2). Therefore, it is possible to filter out at the photoreceiver a specific harmonic that is identical in frequency to the FET oscillation frequency. By splitting the reference signal and transmitting it to many remote MMIC modules, phase coherency between MMIC modules in the phased array is achieved. This part of the IRFFOL has been designed and fabricated, but it has not been evaluated with digital data signals.

The final specifications of the FODL required an RF bandwidth of 300 MHz centered at 750 MHz. This was achieved by introducing a series inductance such that the effective capacitance of the photodiode was reduced and by adding a series resistance of 15 Ω. This matching network augmented the return loss of the photodiode so that over the band the loss was no worse than -2.5 dB and as good as -20 dB. The laser diode matching network was designed to perform over the same bandwidth and yielded a return loss that varied between -7 and -18 dB over the passband. The insertion loss of the complete FODL was nominally 30 dB over the full 300-MHz bandwidth. A more detailed discussion of the IRFFOL technique can be found in references 3 and 4.

Bit-Error-Rate Testing

The ability of the fiber optic data link to carry a digital communications signal was determined through the use of an elaborate bit-error-rate (BER) measurement system. In this test, pseudorandom digital data were transmitted through the link, received, and then checked for errors against a reconstructed set of the original data. The goal of the testing was to allow engineers to correlate the dc and RF operating characteristics of the optical link with the actual digital signal performance. A discussion of the BER measurement system, test configuration, and test results is presented in the following sections.

Digital Instrumentation

The bit-error-rate measurement system used in the testing was designed and built by NASA (fig. 4). In this system, a computer-controlled data generator produces a continuous stream of pseudorandom digital data at a symbol rate of 221.184 Mbps (megabits per second). The data are converted to a burst format by a ground terminal and transmitted at selectable data rates of up to 200 Mbps. The 200-Mbps capability along with the various selectable steps down to the 1.25-Mbps lower data rate limit provide data duty cycles ranging from 0.5 to 90.4 percent. The data are modulated onto a 3.373-GHz intermediate frequency (IF) carrier by a serial-minimum-shift-keyed (SMSK) modulator and are then ready for further frequency translation, transmission, or other processing. After passing through the device under test, the signal is demodulated and sent to a data checker, where a bit-by-bit comparison is made of the received data and a reconstructed set of the original data. The BER performance is then calculated as

$$BER = B_e/B_t$$

This expression quantitatively indicates the number of digital data bits received in error (B_e) per number of data bits transmitted through the system (B_t) in a given period. The modulation format for this experiment

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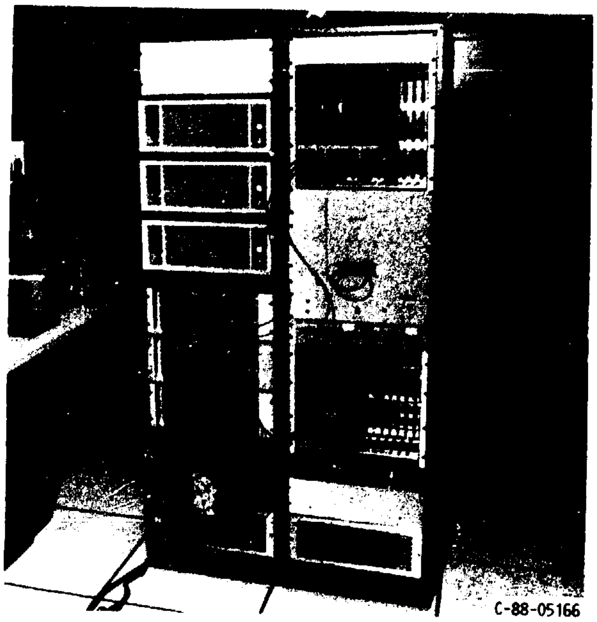

FIGURE 4. - BER MEASUREMENT SYSTEM.

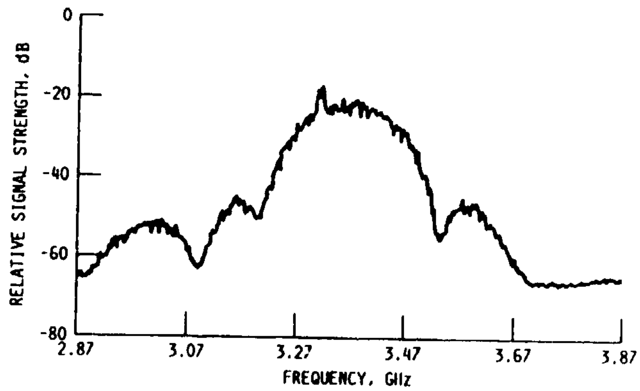

FIGURE 5. - MODULATOR OUTPUT SPECTRUM.

was the same as that used for the Advanced Communications Technology Satellite (ACTS) high burst rate ground terminal. A typical modulated signal spectrum is shown in figure 5.

Test Configuration

A block diagram of the fiber optic data link in the BER measurement configuration is shown in figure 6. In order to perform the BER measurements on the link, the 3.373-GHz test signal needed to be translated down to match the 500- to 1000-MHz passband of the optical components and then translated back to 3.373-GHz for the demodulator. This was accomplished by using downconversion and upconversion mixers as shown in the diagram. One synthesized signal source operated as the local oscillator of both mixers, thereby assuring accurate and coherent translations. Amplifiers, attenuators, and filters were included in the system to adjust the amplitude of the signal and eliminate unwanted mixing products. The fiber optic data link was designed to appear transparent to the test signal; that is, the link could be tested without changing the power levels at any point in the measurement system. This approach provided the greatest measurement accuracy from calibration to actual testing. The only correction that had to be made during the final BER measurements was a compensation for losses caused by the fiber optic link. To simulate these losses, a broadband fixed attenuator was inserted in place of the link during measurement of the baseline system performance. The output power level of the SMSK modulator was approximately -10 dBm. The combined signal and noise powers were received by the demodulator at a nominal power level of -33 dBm.

The ability of a device or system to transmit data without errors is dependant on the relative levels of the signal and noise powers. To control the signal-to-noise ratio (S/N), a noise generation unit was built and added to the system between the modulator and demodulator. White noise power was generated by a solid-state noise source and regulated by a solid-state step attenuator. The noise and test signals were summed by a micro-strip combiner and adjusted to a constant total power with a second step attenuator. By selectively adjusting the attenuation settings in the noise generation unit, a wide range of S/N values could be obtained while maintaining a constant total IF power.

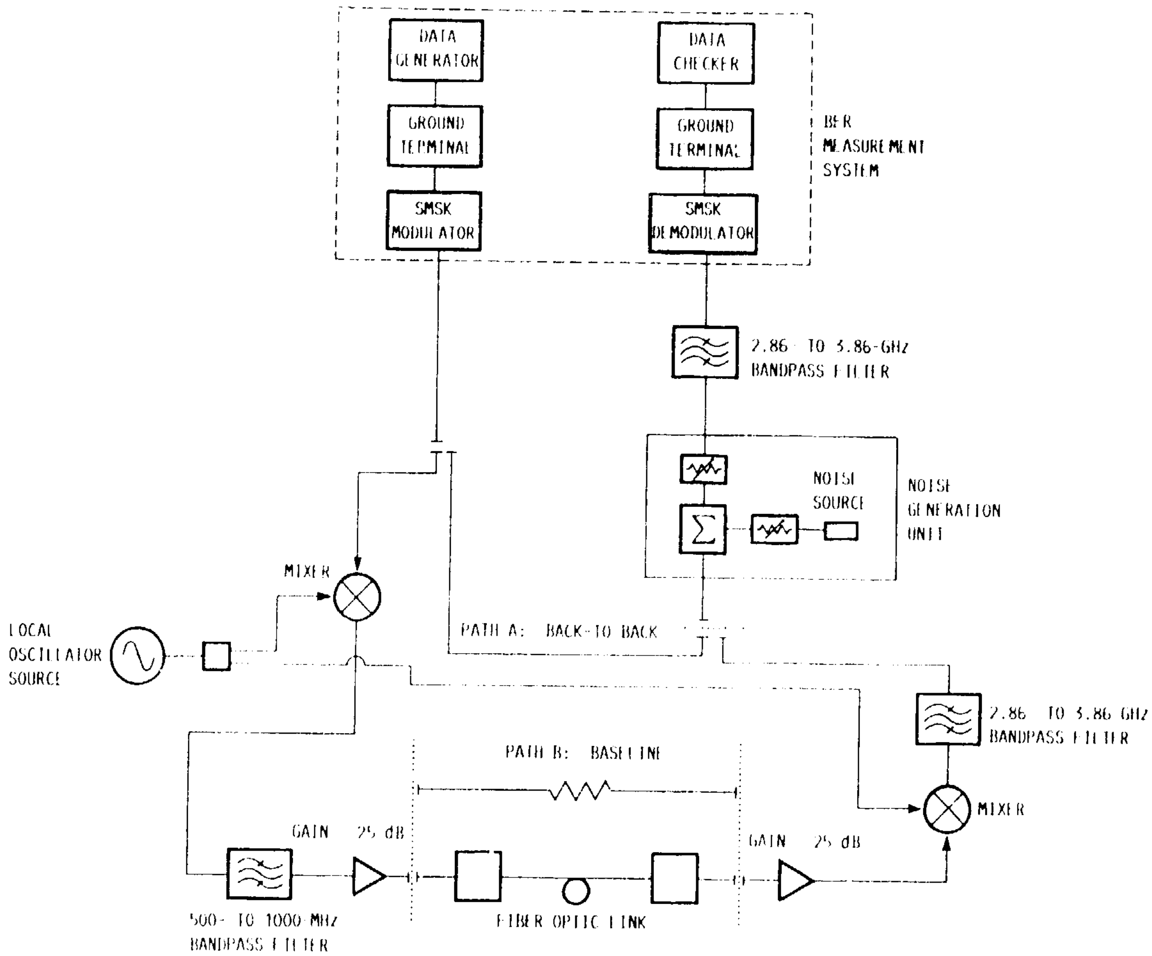

FIGURE 6. BER MEASUREMENT CONFIGURATION.

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 density (N_0). These values, which are based on the system data rate, were calculated in decibels by using the expression

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

where

P_s	measured signal power, dBm
P_n	measured noise power, dBm
D	duty cycle of bursted data, dB
N_{bw}	noise bandwidth of calibration filter; in this case, 379.69 MHz or 85.79 dB Hz
R	symbol rate; here, 221.184 Mbps/sec or 83.45 dB Hz

The E_b/N_0 values, with direct ties to the S/N values, were used as the control parameters throughout the BER testing. The attenuators in the noise generation unit that pro[illegible]oned the signal and noise powers were limited to a 1-dB resolution, but they provided repeatability of better than 0.1 dB over the full range of testing.

Bit-Error-Rate Test Results

Back-to-Back Modem Tests

To verify the accuracy of the BER measurement system, initial testing of the system was done with the modulator-demodulator pair in a back-to-back configuration. This circuit is shown as path A in figure 6. Digital data were transmitted through the circuit, and the BER measurement system began the bit-by-bit checking of the baseband data stream. The results of the data comparison were calculated and recorded by a computer.

The results of the back-to-back modem tests in terms of BER as a function of E_b/N_0 are shown in figure 7. Degradation of performance, displayed on the graph by the BER curve shifting to the right, indicates that a higher S/N (or E_b/N_0) is required to maintain the same bit error level. The curve shows, for example, that for a BER of 5×10^{-7}, an E_b/N_0 of 12.8 dB is required. This curve represents the actual operating performance achievable by the SMSK hardware. The back-to-back BER curve is plotted along with a curve (termed "theoretical") that is based on probability calculations. The latter curve corresponds to the ideal operation of the SMSK modulator-demodulator pair and is offered herein only as a reference point for comparison of the various test results.

Baseline Testing

Once the proper operation of the modulator-demodulator pair had been confirmed, the complete RF test system, with the exception of the optical link, was assembled and tested. This test established a baseline performance level to which the optical link results could be referenced. The test configuration, shown as path B in figure 6, includes all frequency conversion components, filters, amplifiers, attenuators, connectors, and cabling needed for the full-scale testing.

The results of the baseline testing, which are displayed in figure 7, show what appears to be an anomaly in the test data. As presented, the baseline curve appears to have moved to the left of the back-to-back curve; such a move would imply that the additional components added to the circuit are actually improving the quality of the digital signal. In actuality, however, the stability and repeatability of the BER measurement system established uncertainty margins of ± 0.2 dB. The performance of the baseline system falls within this uncertainty range, thereby indicating that the components added to the system in the baseline experimental arrangement do not contribute sufficient degradation to differentiate the baseline system data from the back-to-back data.

Careful attention ensured that power levels remained constant throughout the baseline test system, at the same levels as needed for the fiber optic link testing. Thus, the responses of any power-sensitive devices would not affect the accuracy of the final measurements.

Fiber Optic Link Test Results

The BER performance of the fiber optic data link was tested in two different configurations. In the first configuration, the link was tested with the optical transmitter and optical receiver directly connected, using only the captive fiber pigtails as the transmission media. In the second configuration, the link was tested with 50 m of multimode fiber connecting the transmitter and receiver. For each test, the laser was biased to draw 30 mA of current.

The results of the BER tests for both the short and long data links are presented in figure 8. To achieve a BER of 5×10^{-7}, the baseline system required an E_b/N_0 of approximately 12.8 dB. Introduction of the short fiber optic link into the system produced an immediate degradation of 0.5 dB, thereby requiring the E_b/N_0 to increase to 13.3 dB to maintain the same 5×10^{-7} digital error rate performance. When the 50 m of

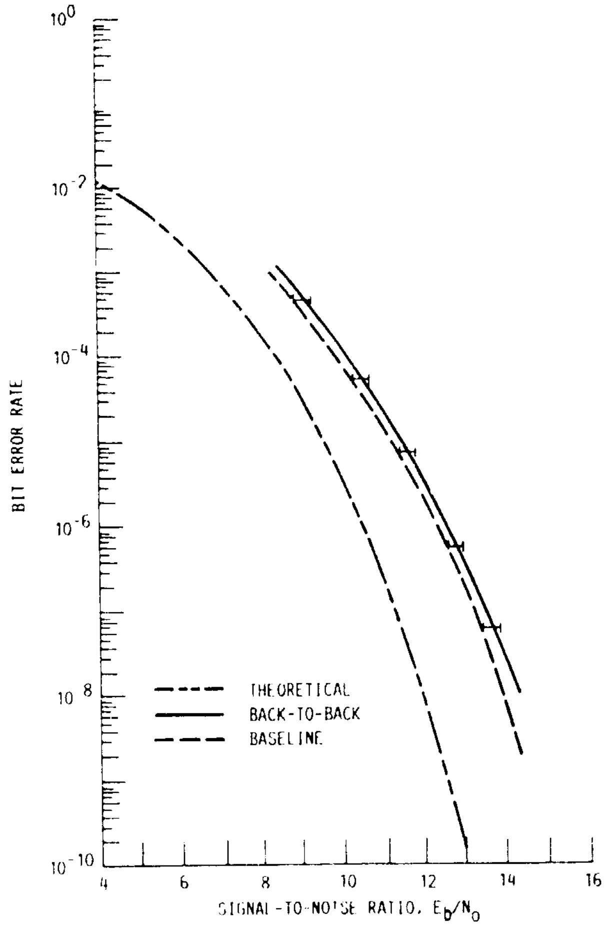

FIGURE 7. - BACK-TO-BACK AND BASELINE RESULTS.

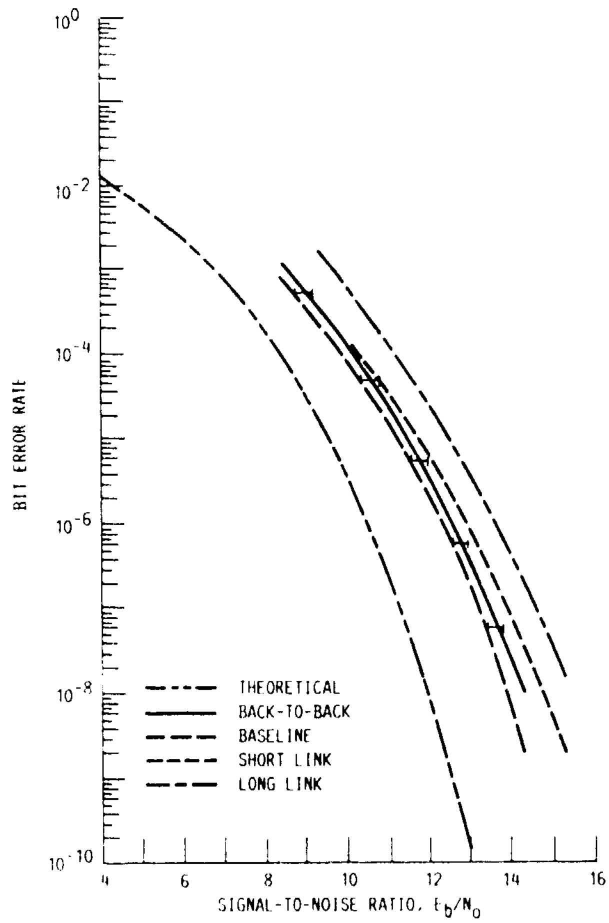

FIGURE 8. - FIBER OPTIC LINK TEST RESULTS.

optical fiber was added to the link, the BER curve shifted even farther to the right, indicating additional degradation of the test signal. Quantitatively, an E_b/N_0 of 13.9 dB was now required to maintain the $5x10^{-7}$ bit error rate; thus the optical fiber imposed a 0.6 dB further reduction in BER performance.

During a review of the operating parameters of the short and long links, we noted that the optical receiver current was higher with the short link than with the long link. This effect is intuitively correct, since the optical power received has been transmitted through only the fiber pigtails and one connector set. Because of the additional insertion loss imposed by the 50 m of optical fiber and the mismatch at the second connector set, the receiver current in the long link case was slightly lower, with the degraded BER performance a likely result. In either case, the E_b/N_0 required for good BER performance, and hence, an effective communications link, was neither unrealistically high nor difficult to achieve in an actual system.

Conclusions

The BER performance of the fiber optic data link discussed herein indicates the promise for fiber optic links in digital communications systems. In addition, incorporating the fiber optic data link into the dual segment injection-locked RF fiber optic link system offers a means to distribute signals to the many radiating elements of a phased array antenna.

As the other components of the optical BFN are fabricated, they, too, can be tested by using the BER measurement system. Once their performances have been assessed, these new components may find their way into various systems and subsystems in the communications networks of the future.

Acknowledgements

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16. Abstract

This paper presents and discusses the measured bit-error-rate (BER) performance of a fiber optic data link to be used in satellite communications systems. In the testing, the link was measured for its ability to carry high burst rate, serial-minimum-shift-keyed (SMSK) digital data similar to those used in actual space communications systems. The fiber optic data link, as part of a dual-segment injection-locked RF fiber optic link system, offers a means to distribute these signals to the many radiating elements of a phased array antenna. Test procedures, experimental arrangements, and test results are presented.

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