COMPARISON OF TWO ARCHITECTURES FOR FIBER OPTIC DISTRIBUTION INSIDE KA-BAND COMMUNICATION SATELLITES

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ABSTRACT

A comparison between two high speed fiber optic (FO) link architectures is presented. Experiments were performed on two reactively matched links, one operating from 18.5 to 19.0 GHz and the other at 0.5 to 1 GHz and then subsequently upconverted to 18.0 GHz. Both links were fully characterized analytically and experimentally. It will be demonstrated that for high frequency operation, the best configuration occurs from the separation of the data and carrier signals. When these signals are sent over separate links, this architecture is called *T/R level data mixing*. Improvements are seen in gain (>30dB), noise figure (>30dB) and dynamic range (>40dB) when this architecture implemented.

INTRODUCTION

Communications systems, radars, and electronic warfare systems can all benefit from the F.O. links currently being developed and employed [1,2]. High speed and ultra-high speed F.O. links will play a particularly important role in the future of data signal distribution in satellites primarily due to the weight and size reduction, which is advantageous to space-bound payloads. When F.O. links with frequencies up to Ka-band and beyond are required, consideration must be given to the architectural format of the link for several reasons.

In addition to low insertion loss, other important performance criteria in millimeter wave fiber optic links are bandwidth, linearity, low noise figure, and wide dynamic range. Satisfying these requirements at high frequencies with the more common *CPU level data mixing* architecture is difficult because of the numerous problems with the laser diode's bandwidth, noise and nonlinearities [3]. In this scheme, the data signal and carrier are mixed before being used to modulate the laser diode's bias current. An alternate architecture, called T/R level data mixing, or remote data mixing, requires that the carrier and data signals be sent over separate links and then mixed after optical detection. This configuration shows more promise for high speed operation because the data link can be operated in a linear and low noise regime while the carrier link can be optimized for single frequency operation.

The advantages of using the T/R level data mixing architecture have been demonstrated at a carrier frequencies of 6.5GHz [3] and 24GHz [4]. An improvement in system sensitivity of 22dB was gained over the CPU level scheme by using non-reactively matched transmitters and receivers in the 6.5GHz system. Further improvements in gain of up to 20dB were predicted when improved optical coupling and reactively matched components are used.

This paper demonstrates the best performance possible using optimized link for the CPU level architecture operating from 18.5 to 19.0 GHz. The characteristics of this architecture are compared experimentally and analytically. The results of this link will be compared with the measurements of an optimized T/R level data mixing architecture operating over the same frequency range. Furthermore, the results which are being presented can be extrapolated to much higher frequencies when laser harmonics and oscillator nonlinearities are used subharmonically to injection lock the local oscillators in the T/R modules [5].

The T/R level data mixing link used in this comparison was similar to one previously developed at Drexel [6]. Further improvements in the transmitter and receiver modules have produced a much better link gain of -3dB as compared to the previous value of -35dB. Noise figure and compression dynamic range were measured and were found to be 45dB and 79dB/MHz respectively. The output of this link was mixed with an 18GHz local oscillator to complete the T/R level architecture. Additional noise contributions were negligible and the gain decreased by 15dB due to the mixer conversion loss.

EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The 18.5 to 19.0 GHz link modules employed GTE high-speed lasers and photodetectors. The lasers were 1.3µm, InGaAsP VPR-BH structures with 3dB electrical bandwidths of approximately 19.0GHz [7]. Photodetectors were InGaAs, rear illuminated mesa structures with bandwidths in excess of 22GHz [8]. Both devices were fully characterized and 4 section reactive-stub matching circuits were designed for each. Circuits were fabricated on 10 mil alumina substrates and incorporated ample tuning mechanisms to account for the variations in individual device impedances.

Coupling to the laser was accomplished through the use of on fiber lenses fabricated at Drexel. These multimode fiber lenses were created by etching the bare fiber to form a 800µm long taper. The taper was heated in a fusion splicer to smooth surface defects and to create a small hemispherical tip to further enhance the light gathering capability [9]. Light coupling improved by 6dB over that obtained with a straight cleaved fiber. A straight-cleaved 50µm core fiber was butt-coupled to the detector to achieve coupling percentages approaching 90 to 95 percent.

Gain measurements were performed on an HP8510B network analyzer. A Tektronix 2756P spectrum analyzer was used for two-tone intermodulation distortion tests and noise measurements. All link measurements were performed with a 50 meter length of Siecor 50/125µm fiber between the transmitter and receiver modules.

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THEORETICAL ANALYSIS OF LINKS

The reactively matched transmitter and receiver modules connected by a length of fiber can be modeled using S-parameters in the following representation [10]:

$$\text{Gain} = H_L^2 \frac{|S_{21L}|^2 |S_{21D}|^2 (1 - |\Gamma_{LASER}|^2)(1 - |\Gamma_{DETECTOR}|^2)}{(1 - S_{22L}\Gamma_{LASER})^2 (1 - S_{11D}\Gamma_{DETECTOR})^2}$$

Where the optical losses are represented by the term:

$$H_L^2 = L^2 \eta_L^2 \eta_D^2 K_L^2 K_D^2$$

where L is fiber losses, H_L and H_D are the responsivities, and K_L and K_D are the light coupling coefficients of the laser and detector respectively. The terms Γ_{LASER} and $\Gamma_{DETECTOR}$ are the reflection coefficients of the junction resistances of the laser and detector. In this F.O. link representation, the matching networks and parasitic elements for each device are grouped into two port networks. This provides for the correct calculation of the amount of rf power which is actually delivered to the areas of the devices which take place in the electro-optic/opto-electronic conversion process.

Likewise, the various F.O. link noise contributions can be calculated from this model. Contributions include laser RIN power, shot noise from the detector, and finally the thermal noise of the transmitter and receiver circuits and devices. Each noise contribution is listed below.

$$N_{RIN} = RIN(f)\,(I_b - I_{th})^2\,(\eta_L K_L L K_D \eta_D)^2\,BxZ$$

$$N_{shot} = 2e\left[(I_b - I_{th})(\eta_L K_L L K_D \eta_D) + I_d\right]BxZ$$

$$N_{thl} = 4KT_a B\,(\eta_L K_L L K_D \eta_D)^2\,Re\{Y_{thl}\}xZ$$

where Z is given as:

$$Z = \frac{|S_{21D}|^2}{|(1 - \Gamma_{SD} S_{11D})|^2} \times 50$$

$$N_{thd} = 2KT_a B\left(1 - |\Gamma_{in}|^2\right)$$

The dominant noise mechanism in the short-haul fiber optic link is the laser relative intensity noise. For longer links, the shot noise would begin to dominate. Link noise figure can be calculated from the sum of the noise contributions and from the input kTB noise to the link. Noise figure is calculated as follows:

$$N_{IN} = kTB$$

$$N_{OUT} = N_{Shot} + N_{th} + N_{RIN}$$

$$NF_{Link} = \frac{(SNR)_i}{(SNR)_o} = \frac{P_{in} * N_{out}}{P_{out} * N_{in}} = \frac{1}{G_{Link}} * \frac{N_{out}}{N_{in}}$$

Lastly, we can calculate the compression dynamic range (CDR) from knowledge of the noise figure and the 1dB compression point of the laser diode. The minimum detectable signal (MDS) is a function of the thermal noise, link noise figure and the bandwidth to which the noise is referenced and is given as:

$$MDS = -174 + NF_{LINK} + 10\log_{10}(BW)$$

$$CDR = P_{1C} - MDS$$

Obviously, gain, noise figure, and dynamic range are related to one another. From the above equations, it can be seen that maximization of link gain should improve both the noise figure and the dynamic range. Unfortunately, degradation of the system will inevitably occur at higher frequencies close to the laser 3dB bandwidth, where RIN noise is highest near the relaxation oscillation frequency. Therefore, the CPU level architecture will be limited in dynamic range and will experience higher noise power levels than the T/R level architecture.

SIMULATED AND MEASURED RESULTS

Gain measurements for the optimized 18.5 to 19.0 GHz CPU level link were performed at several laser bias levels. Results of simulated and measures responses are shown overlaid in Fig.1 for a 70mA laser bias. At low frequencies, up to approximately 8 GHz, the simulation model predicts the experimental results quite well. Unfortunately, at the frequencies of interest, there was no measured gain peak. Further measurements were performed on a spectrum analyzer which allowed for the viewing of the low intensity signal. A gain peak was finally recorded at 18.75GHz with a level of -68dB.

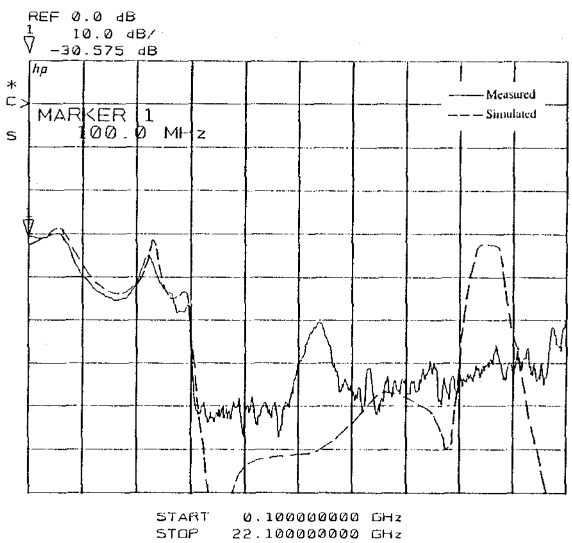

Fig. 1. Simulated and experimental gain of reactively matched 18.5 to 19.0 GHz fiber optic link.

Upon further inspection, the reactive matching circuits were found to be radiating at frequencies primarily above 8GHz. Plots of radiated power vs. frequency were obtained using a rigid coaxial probe which was scanned over the surface of the circuits. On the basis of these plots, the radiative power loss was determined 18.75GHz for the transmitter and receiver circuits. When the total 34dB radiative loss was added to the simulated gain value at 18.75GHz, the measured gain was obtained. This indicates that the circuit models used in the link analysis were correct in predicting the relative circuit responses, but the matching circuit design process could not anticipate the radiative effect.

Two-tone intermodulation distortion tests were also performed on the CPU level link and the results for 18.75GHz are shown in Fig. 2. for a laser current bias level of 80mA. Since the majority of power was radiated in the transmitter circuits before reaching the laser diode, a high level of input power, 16dBm, was required to reach the 1dB compression point. A third order intercept of 27dBm was calculated from the measurement. Theoretical intercepts are given in Table I.

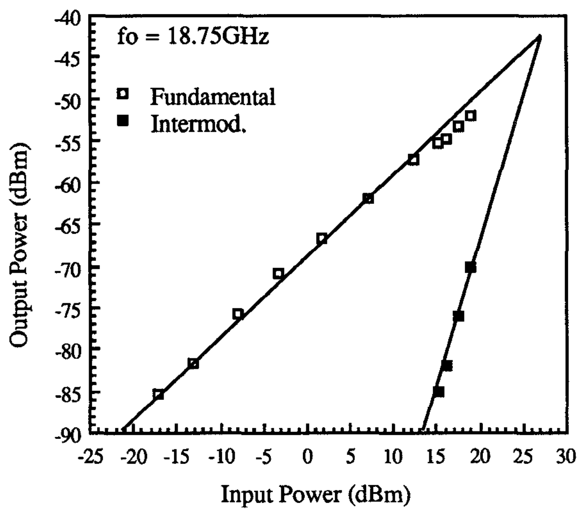

Fig. 2. Intermodulation Distortion results for 18.5 to 19.0GHz link. Third order intercept is at +27dBm. Laser bias current is 80mA.

Lastly, various noise contributions were calculated based on previously given equations and these contributions are shown in Fig. 3. From the noise contributions, theoretical noise figure, displayed vs. frequency in Fig. 4, was also calculated. As expected, RIN is the dominant noise source. Also, the noise figure of 77dB, is about 40dB greater than what would be for a T/R level architecture even when the link was optimized over the bandwidth of interest.

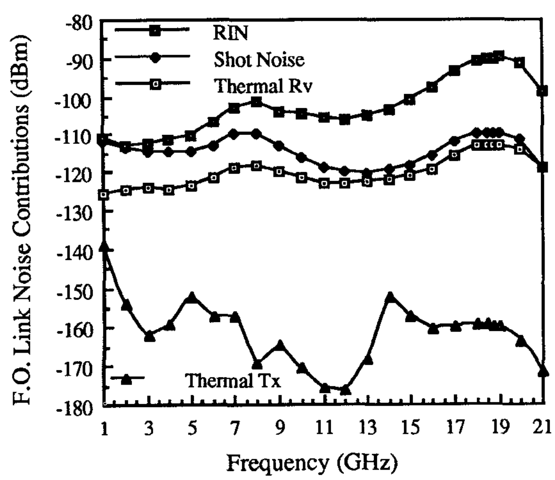

Fig. 3. Various theoretical noise contributions for the 18.5 to 19.0 GHz CPU level fiber optic link.

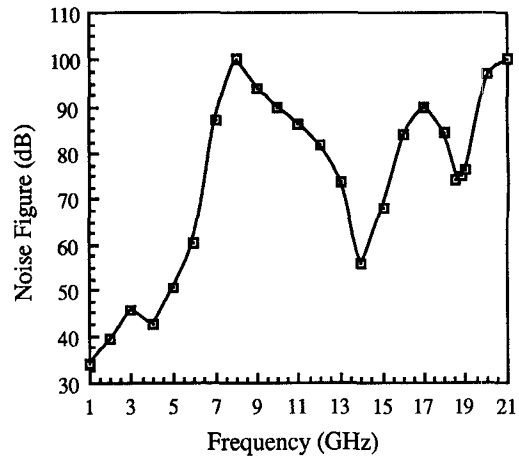

Fig. 4. Theoretical noise figure for the 18.5 to 19.0 GHz CPU level fiber optic link.

EVALUATION OF LINK ARCHITECTURES

Summarized in Table I are the relevant figures of merit for the 18.5 t o 19.0 GHz CPU level data mixing link. Although the link did not perform exactly as simulated, sufficient confidence in the modeling process exists based on the radiation measurements and subsequent simulation with radiation. Thus, with a better matching circuit topology, the simulated results should be easily attainable.

Table I. Results of 18.5 to 19.0 GHz CPU level F.O. Link (Results given at 18.75 GHz)

	Simulated w/o Radiation	Measured	Simulated w/ Radiation
Gain	-33dB	-68dB	-67dB
Output Noise Floor Level for kTB	-130dBm	*	N/A
Intermod. Intercept Point	+21dBm	+27dBm	+27dBm
Dynamic Range	37dB/MHz	*	N/A
Radiation loss	N/A	-34dB	N/A

* not able to be calculated because of low F.O. gain

From the CPU level configuration's results, it is evident that for this type of link architecture, the dynamic range is compromised by laser noise. This is a consequence of operating the laser near the 3dB bandwidth frequency of 19.0GHz. Because of the limited bandwidth of currently available high-speed lasers, this result will be typical of all CPU level links. Also, with the smaller sizes of these high-speed devices, additional problems such as more difficult coupling and reduced device responsivity decrease the potential link gain.

Conversely, the T/R level link with its measured gain of approximately -3dB, before being up-converted to 18GHz, takes advantage of a relatively inexpensive and low frequency laser whose RIN peak is outside of the operating bandwidth. Also, the process of mixing the local oscillator signal and the data signal in the T/R level scheme will not add significantly to the noise of the system, nor should it decrease the dynamic range. All of these facts indicate that the best F.O. link performance can be achieved through optimization of the data link when the T/R level data mixing architecture is implemented.

CONCLUSIONS

Overall, the above analysis indicates that operating very high speed lasers near their 3dB electrical bandwidth frequency, in the CPU level scheme, produces excessive noise and contributes to an increase in link insertion loss as well as a decrease in dynamic range. The performance of the alternate architecture of T/R level data mixing is characterized primarily by the performance of the data link. And, with improved matching circuit technology and light coupling techniques, zero-loss links can be designed to transmit data signals, thus improving the overall link performance significantly. Additionally, less than ideal lasers can be used to send relatively noisy carrier references over an additional link without seriously affecting the overall T/R level link performance.

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