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P. Hall

Measurement of Fiberoptic Link Performance

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Abstract: Lab measurements of the performance of the fiberoptic link used between the antennas and control building have been made to verify that they have sufficient dynamic range to carry a bandwidth of 8 GHz. Assuming that all the units are similar to the one tested, this bandwidth can be transmitted with better than 1% linearity and less than 1% added noise provided optical losses are less than ~15 dB.

1. Introduction

A fiberoptic system is used to carry the IF signals from the receivers to the control building and to implement the longer delay segments (up to 512 ns). Ortel 3530A 10 GHz Fiberoptic Transmitters are used in the antennas and Sumitomo #62-3300-7423 single-mode fibers carry the signal to the control building. Three fiber delay stages are currently implemented using SPDT fiberoptic switches, and the signals are detected by Ortel 4515A 10 GHz Fiberoptic Receivers followed by low-noise amplifiers (Miteq AFS4-00500500-20-10P-4).

Currently two 1-GHz channels are multiplexed on to the fiber transmission system but this will be expanded to one 4-GHz channel or two 2-GHz channels, and later two 4-GHz channels. This puts tighter constraints on the dynamic range of the link. The dynamic range, defined by the noise floor and the gain compression of the link, should be adequate at the level of a few percent in order not to degrade system performance. Measurements on one of the existing links have been made and compared with the design calculations to verify that the system will handle the wider bandwidth.

2. Design Calculations

Ortel, the manufacturer of the fiberoptic link receiver and transmitter, provide a comprehensive design guide [1] which has been very helpful in preparing this document. I have also had a lot of useful information from Steve Padin. The system tested in the lab comprised the transmitter and receiver racks. The transmitter chassis contains only the fiberoptic transmitter module (S/N 1476), power supplies and monitoring electronics. In the receiver chassis there are the three delay segments (128, 256, and 512 ns) followed by the fiberoptic receiver (S/N 0421) and low-noise amplifier (S/N 233565).

2.1 Link Gain

The link consists of the laser transmitter, connecting fiber, delay lines, photodiode and low-noise amplifier. The laser diode has a low impedance which is matched using a series resistance to have a return loss greater than 9.6 dB. It has a modulation efficiency, η_{Tx}, which is about 0.1–0.2 W A^{-1} for the Ortel transmitter. Between the laser diode and photodiode there is an optical power loss, L_{opt}, in the fiber, optical connectors, and delay lines. The photodiode in the receiver has a quantum efficiency of η_q so that its responsivity will be $\eta_q\beta$. β is the responsivity of a perfect detector (one electron per photon)

$$\beta = \frac{e}{h\upsilon} \tag{1}$$

e is the electronic charge, h is Planck's constant, and ν is the laser frequency. β is about 1.057 mA mW^{-1} for a laser wavelength of 1310 nm and η_q is about 0.71 for the Ortel receiver. The photodiode output impedance is high and it is matched to 50 Ω with a resistor in parallel. Precise values for the diode impedance are not given by Ortel but we will assume that the diode resistance is infinite. Taking the transmitter input impedance and the receiver output impedance with the matching resistors to be the same (nominally 50 Ω) the total effective RF loss of the link becomes

$$L_{link} = \frac{4L_{opt}^2}{\left(\eta_{Tx}\beta\eta_q\right)^2} \tag{2}$$

The factor 4 arises because of the receiver photodiode matching resistance, and L_{opt} appears quadratically since the RF *amplitude* modulates the optical *power*. For no optical loss the link loss is about 28.5 dB, and for 10 dB optical loss the link loss is 48.5dB.

2.2 Noise Mechanisms

In the documentation for the fiberoptic link Ortel specify a noise due to the laser, although the mechanism is not explained. This noise, P_{laser}, is of the order of -125 to -110 dBm/Hz referred to the transmitter input and is dependent on the RF frequency. Noise due to photon statistics is also present and is calculated from Poisson statistics to be

$$P_{photon} = \frac{2h\nu P_0 R_{RF}}{\eta_{Tx}^2\eta_q} L_{opt} \tag{3}$$

P_0 is the laser output power, and R_{RF} is the receiver RF impedance (50 Ω). In a more detailed theory the noise from a laser does not follow Poisson statistics and the photon noise could be higher, typically by 20% [2] . If there is no optical loss this gives an equivalent input noise (EIN) of -140.7 dBm/Hz for a laser power of 4 mW.

Finally, there is noise due to the receiver, mainly the thermal noise in the matching resistance and the noise of the RF amplifier. The EIN is

$$P_{th} = k(T_{res} + T_{amp})L_{link} \tag{4}$$

where T_{res} is the physical temperature of the diode matching resistor and T_{amp} is the amplifier noise temperature. For an amplifier with a noise figure of 1.5 dB (T_{amp} = 120 K) P_{th} is about -146 dBm/Hz in the absence of optical loss (L_{link} = 28.5 dB). This will increase as the square of the optical loss.

From the above we see that the noise is dominated by the laser noise when the optical loss is small (≤ 10dB) and for higher losses the thermal noise becomes more significant. Photon noise is never a dominant noise mechanism. In the millimeter array the optical loss is typically on the order of -10 dB, but since the degradation of the amplifier effective noise is proportional to the square of the optical loss, care needs to be taken to keep all the optical connections in good condition.

3. Measurements

A series of measurements on a fiberoptic link was made in the lab to verify the above calculations. The transmitter was connected to the receiver with a fiber about 4 m long. These measurements included the optical delay lines with their associated optical switches.

3.1 Gain

The laser power was measured using an HP 8153 optical power meter to be 3.38 mW. The difference between this and the specified 4 mW minimum may be due to losses in the fiber connectors. When the transmitter and receiver were connected the photocurrent was 0.62 mA. Assuming an efficiency of 0.75 mA mW^{-1} for the receiver diode gives a received power of 0.83 mW and an optical loss of 6.1 dB. A direct measurement using the optical power meter gave ~9 dB. The difference may be partly in the accuracy of the laser power measurement and partly in the assumed value of the photodiode efficiency. Another fiberoptic cable gave a lower loss, which was measured with the power meter to be ~6 dB. This was used in subsequent measurements

An HP 8720B Network Analyzer was used to measure the link gain, with and without the RF amplifier. The results are shown in Fig 1. The amplifier has a nominal frequency coverage of 0.5–5.0 GHz. As shown in the graph, the link without the amplifier has a loss of about 43 dB which is reasonably flat across a bandwidth of 10 GHz. It is in satisfactory agreement with the expected value of 40.5 dB for 6 dB of optical loss. There was negligible dependence on the number of delay segments inserted.

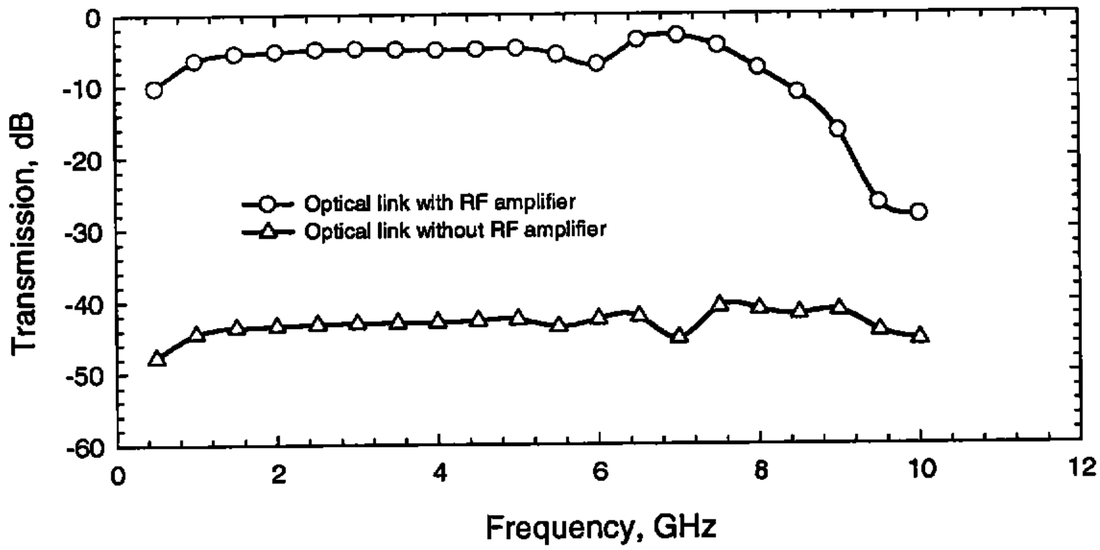

Fig. 1: Measured transmission through the optical link with and without the amplifier.

Fig. 2 shows the measured input VSWR. Typically it is below 2:1 but it rises above specification at the low end of the band.

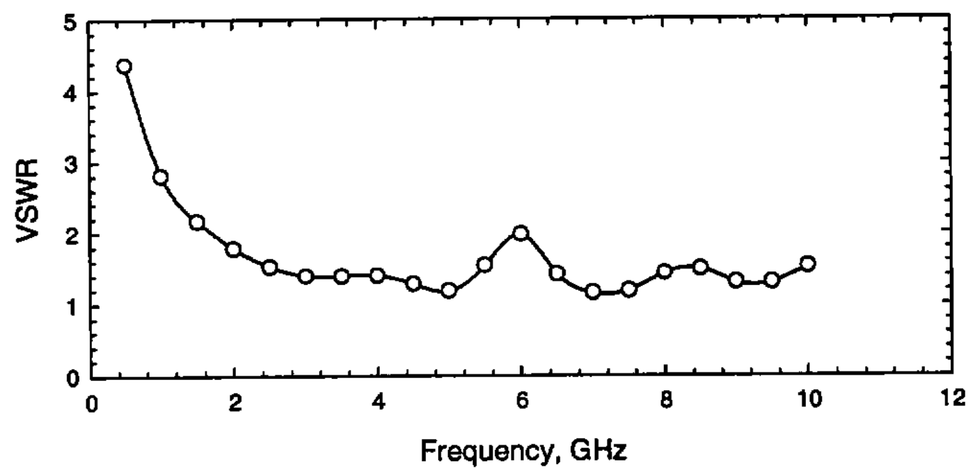

Fig. 2: VSWR into the fiberoptic transmitter.

3.2 Noise

Noise measurements were made using an HP 8564E Spectrum Analyzer. The analyzer noise floor was at least 20 dB below the noise measured at the output of the link. Noise spectral density was measured at the amplifier output with the laser power off and then again with the laser turned on. Using the measured amplifier gain and cable losses these were referenced to the amplifier input (*i.e.*, the output of the optical receiver). Fig. 3 shows these measurements. Good agreement is found between the measurements and the noise calculated with the laser off. With the laser turned on the noise rises by 1.8–11.5 dB, showing that with the existing optical loss the total noise is still dominated by the laser noise.

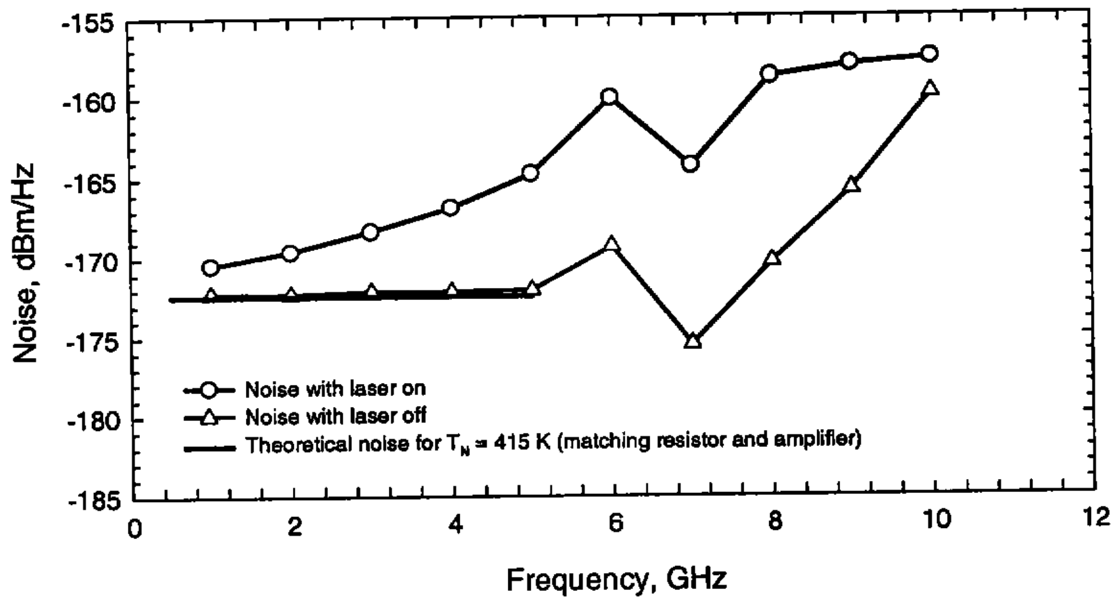

Fig. 3: Noise referred to the input of the RF amplifier.

Fig. 4 gives the noise measured at the output of the link with the laser on, as well as the value converted to an EIN. Also plotted is the specification for the laser noise given by Ortel showing that, including all noise sources, the measured noise is less than specification for just the laser noise.

3.3 Linearity

Five Mini-Circuits ZFL-2000 amplifiers (1–2 GHz) were cascaded with a 50 Ω input load produce a Gaussian noise input. These were connected to the transmitter RF input *via* a step attenuator and isolator. A 10-dB coupler was used to monitor the input level. Power was measured with an HP 435A Power Meter which could be switched with a coaxial relay between the link output (after the RF amplifier) and the coupler on the link input. Up to 11 mW could be applied to the link input. The maximum allowable power is not clearly specified by the manufacturer, though a limit of 60 s for +20dBm input is given.

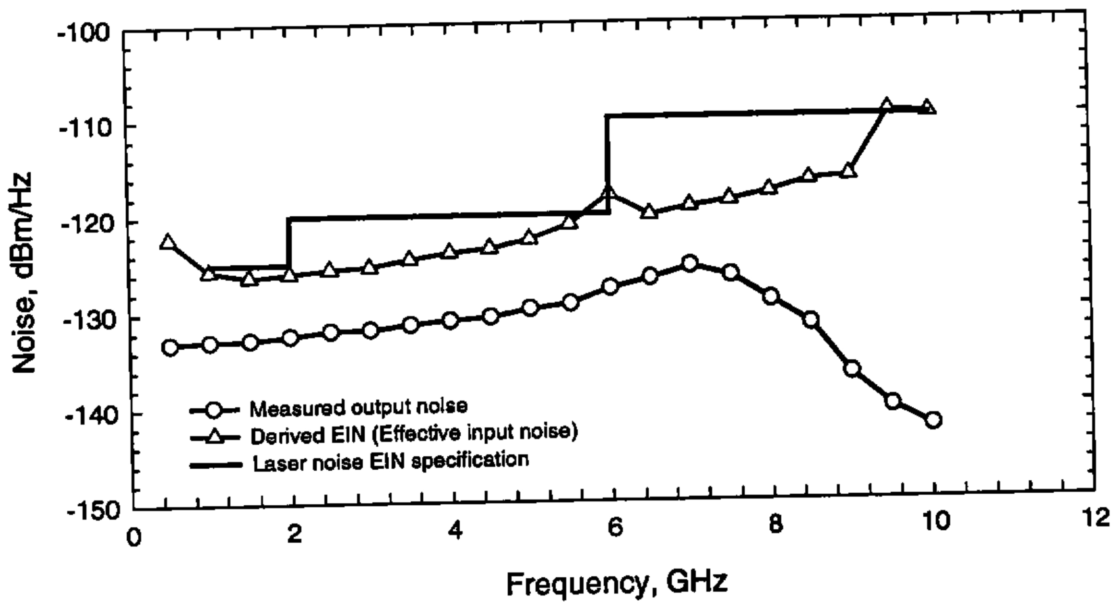

Fig. 4: Noise of the link referred to the link input. The specification is the upper limit due to laser noise only.

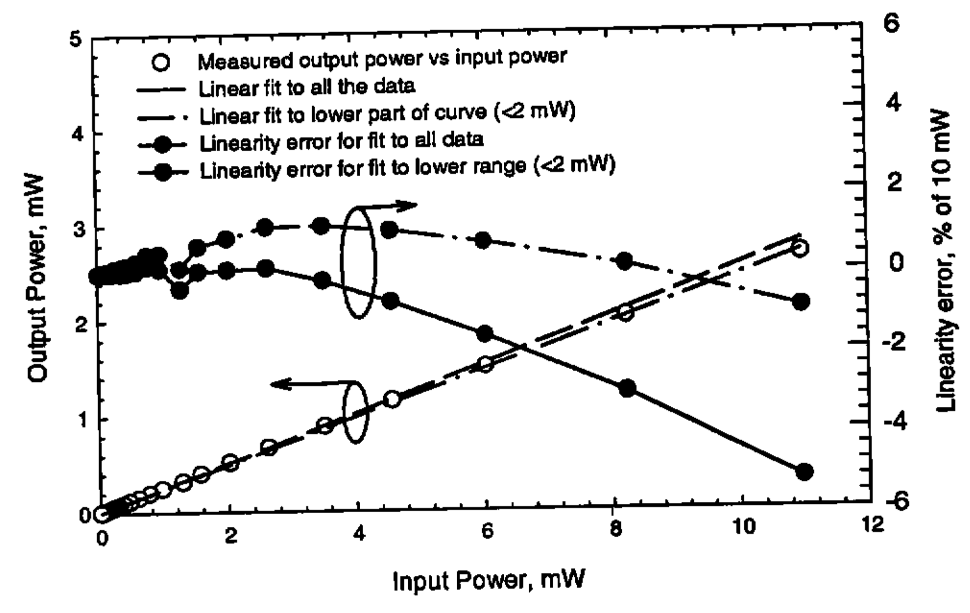

Fig. 5: Linearity measurements of the link. One fit was made to the linear portion of the data, and another to the whole range.

After subtraction of the link noise from the output power the response is as shown in Fig. 5. Two linear fits were made, one for input power levels ≤ 2 mW, and one using all the data. Departures from linearity are also shown on the graph, and it can be seen that the linearity should be within approximately ±1% for power levels up to at least 10 dBm.

4. Conclusions

To keep the link linearity better than ~1% and to avoid putting too much power into the laser diode the total RF power should be ≤10 dBm. Over a bandwidth of 8 GHz this corresponds to power spectral density of -89 dBm/Hz. If the optical losses in the link can be kept small the noise performance is dominated by the laser noise. This noise is a function of the RF frequency, but is generally less than -110 dBm/Hz. Even with an optical loss of ~15 dB this will only rise to ~-109 dBm, giving a 1% contribution to system noise. In practice the 10 dBm will correspond to the receivers looking at ambient temperature loads and the power while looking at the sky may be a third of this. However, over most of the band the link noise is much less than -110 dBm/Hz so can be expected to be less than 1% of the total, even under good conditions.

References

[1] *A System Designer's Guide To RF and Microwave Fiber Optics*, Ortel Corporation, 1997.

[2] H. M. Nussenzveig, *Introduction to Quantum Optics*, New York: Gordon and Breach, 1973.