GBT MEMO 183

National Radio Astronomy Observatory
Green Bank, WV

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MEMORANDUM

To: Addressees

From: S. White and R. Norrod

Subject: **Status Report: GBT Fiber IF System**

Since GBT memo number 151 was written in June 1996, much additional testing and research into the gain stability properties of analog optical fiber microwave links has occurred. The purpose of this memo is to provide a status report on the laboratory results and indicate future directions in order to achieve a practical fiber IF system design for the GBT.

Photodiode Receivers

Several photodiode types have been evaluated for polarization sensitivity. Table 1 summarizes the polarization sensitivity of the all the receivers tested. The photodiode receiver with the best performance measured to date is the New Focus 1414, which uses a bottom-illuminated type diode with the fiber end butted against the photodiode, and a large fiber polish angle of 12 degrees. From our tests and analysis, the polarization sensitivity appears to be a function of the angle of the fiber polish at the glass-air boundary, the distance between the photodiode surface and the end of the fiber, and the type of photodiode in the detector (either top-illuminated or bottom-illuminated). The New Focus models 1414 and 1434 illustrate the difference in diode types, with the bottom-illuminated diodes being approximately a factor of two less sensitive. Deducing the mechanism of polarization sensitivity is complicated by the various couplings of the light to the photodiode among the different models. However, the technique of butting the fiber directly to the photodiode used in the 1414 appears to reduce the polarization sensitivity significantly.

Another important consideration is the return loss of the photodiodes. The New Focus and HP diodes were tested with FC connectors. With FC connectors which have a return loss of approximately 30 dB, care must be taken to isolate the laser from the fiber. The internal isolator in the DFB laser was not adequate when the return loss of the receiver was less than 45 dB. Testing of these photoreceivers required an additional isolator to obtain the results in Table 1. In the final system design, multiple reflections and reflections back into the laser cavity must be minimized.

Polarization Maintaining Fiber

Two types of polarization maintaining fiber where tested, the 3M brand and the Corning Panda fiber. These fibers are specified by the ratio of power in orthogonal axes at one end of the fiber when linear polarized light is launched into only one axis at the other end, the "h-parameter". However, the change in h-parameter is not specified when external stresses are applied to the fiber. The tests in the lab and on the 140 ft where designed to measure the effects from a change in h-parameter under movement. Table 2 gives the h-parameter specification for the PM fiber and the estimated extinction ratio for the cables purchased. As reported in memo 151, a ten meter length of 3M fiber was tested, giving an improvement factor of about 60, justifying a purchase of 120 meter lengths of Panda and 3M fiber to be tested on the 140-foot telescope.

To achieve a stable state of polarization through the fiber, linear polarization must be launched down only one of the PM fiber axis. Since all our laser transmitters are equipped with SM fiber pigtails, the polarization state of the light leaving the laser pigtails is unknown, and is subject to change due to stresses on the SM pigtail. This uncertainty in the polarization state along with the reduction of extinction ratio in the mating of fiber optic connectors hampered our testing of the PM fiber. However, on occasions when the state of polarization was presumed linear and launched down the "slow" axis of the 120 meter length of Panda fiber, the polarization sensitivity was improved by a factor of 30 under fiber movement. The improvement was observed in laboratory tests and was repeatable over several hours. The 120 meter length of 3M fiber was never as stable as the Panda in the lab or on the 140-foot and measurements of this fiber were always suspect. One of the connectors of the 3M appeared to be defective; therefore, the fiber was sent back to the factory for replacement of the connector. The fiber was then installed on the 140 foot, but no improvements in stability were observed.

Assuming Panda fiber and a length of 222 meters (the approximate length needed on the GBT), the maximum extinction ratio obtainable would be 26 dB without connectors, which is about the same as the 10 meter length of 3M with connectors. Therefore, a reasonable assumption is a factor of 60 improvement in polarization sensitivity due to telescope movement with Panda fiber on the GBT. This would require all laser diode modulators to be equipped with a PM fiber pigtail. Since connectors would significantly degrade the performance, access to a special fusion splicer to install the PM fiber, lasers, and photodiodes would be required.

During testing of the PM fibers on the 140-foot, unexplained changes in the detected total power were observed. This may have been due to slow changes in the laser polarization state, some inherent effect in the PM fiber, or because of problems due to connectors.

Considering the problems of fusion splicing the PM fiber, the high cost (about $36/meter for PM vs. 20 cents/meter for SM fiber) for the improvements achievable, at this time the PM fiber is not considered a practical solution.

<u>Polarization Scrambler</u>

Certain commercial fiber communication systems incorporate polarization modulators to "scramble" the polarization state launched down the fiber. Some studies and experimentation has been done to determine whether such a technique would be applicable to our needs. We were able to borrow at no cost a polarization modulator from Lucent technologies to use in our experiments.

The polarization modulator continuously changes the state of polarization in a way best described as a great circle on the Poincare sphere. The polarization of the light goes through all the states on the great circle twice in one period of the modulating signal, effectively de-polarizing the light on time scales much longer than the period of the modulating signal. The modulator borrowed from Lucent technologies was optimized at a wavelength of 1500 nm; therefore, the performance was degraded somewhat at 1300 nm used in our system.

The improvement in polarization sensitivity with the polarization modulator was found to be inversely proportional to the degree of polarization. Due to the quirks of optimizing the device at 1500 nm and operating at 1300 nm, the degree of polarization (DOP) was 50% with no modulating signal applied. The manufacturer of our borrowed device indicated that the minimum DOP achievable in our tests was 9% with the modulating signal applied. Our tests showed that with no modulating signal applied, the measured polarization sensitivity improved by a factor of 2, while with the minimum DOP, the sensitivity improved by factor of 10. The minimum DOP available from an optimized device is stated by the manufacturer as approximately 3%. Therefore, the maximum improvement that can be expected from a polarization modulator is probably a factor of about 30. Cost of these devices is about $6K each.

Since the photodiode detector is a polarization sensitive device, the continuously changing state of polarization produces amplitude modulation. Thus spurious signals in the photodiode output are produced at harmonics of the modulation signal. The amplitude of the harmonics depend upon the orientation of the photodiode to the states of polarization of the light at the output of the modulator. Therefore, movement of the fiber changes the amplitude of the harmonics, and this effect was observed in our tests. The presence of these changing spurious signals is probably not acceptable in our IF system, effectively eliminating the polarization modulator as a solution.

Automatic Gain Control

Several approaches to achieve automatic gain control of the fiber IF links are being considered, and some preliminary lab tests have been done. In order to implement such a system, some quantity which measures the link gain must be available, and connected via a control circuit to a gain-control element. Since the laser diodes are DC biased to an operating point before modulation is applied, the photodiode average output current provides a measure of the link gain *assuming that the laser operating point is stable.* Alternatively, a stable RF pilot tone at a frequency outside the normal IF passband (e.g. 10 or 50 MHZ tones) could be injected into the IF chain and the detected level used as a control signal. Lab tests with a constant RF signal level into a fiber link confirms that the photodiode average current indicates changes in the optical loss or changes in the photodiode sensitivity due to changes in the light polarization. An advantage of an AGC approach is that it could correct for effects besides just polarization changes causing gain changes.

Because of the broad IF bandwidth (7 GHz) we hope to support in the GBT IF system, we feel that the gain control element should be located in the optical path, not the microwave part of the system. It would be difficult, if not impossible, to construct a microwave component such that its loss or gain varies perfectly uniformly over the 1-8 GHz band, and unacceptable spectral-line baseline structures would otherwise be introduced by the control loop. We have constructed a mechanical optical fiber variable attenuator which works by purposely introducing micro bending losses in a fiber by controlling its wrap around a fixed diameter rod. Experiments with this variable attenuator confirms the approach works, however it appears that the attenuator introduces polarization dependent losses (PDL) and also has poor repeatability. While these limitations might not be critical or could be corrected, before putting much additional effort into a mechanical attenuator design we would like to consider instead using electronic control of a laser operating point and an external modulator.

It appears now that the use of externally-modulated laser systems are becoming economically competitive with direct-modulated lasers. The externally-modulated systems may be attractive for two reasons: first, they appear to have superior noise performance; second, controlling the laser operating point in these systems provides a means to electronically control the RF gain through the link. However, there are a few technical concerns that must be investigated. There are concerns about the modulator internal stability, its linearity performance, and the RF drive level required. These factors could determine the practicality of their use in our systems.

Laser Control Circuits

Our lab experiments have convinced us that the typical laser ALC and temperature-control circuits standard in commercial packaged laser transmitters are not sufficiently stable for our requirements. Third-party precision controllers claiming to be a factor of 1000 less sensitive to temperature are available at reasonable prices; if these are not satisfactory NRAO may have to design precision controllers.

Optical Connectors

Experience with optical connectors, primarily the angled low-reflectance types recommended for analog links, has convinced us that our system should be designed with no in-line optical connectors. They can exhibit high temperature sensitivity, PDL, and microphonics, and we feel that their convenience does not justify the possible performance degradations associated with their use. Fusion splices can be made fairly quickly when components need to be replaced, and so we plan to design the IF system as a direct point-point connection between the receiver and equipment rooms, using only fusion splices and no in-line fiber connectors.

Cable Wraps

The GBT azimuth wrap provided by the contractor is a "maypole" type design (540 degrees of travel is required). A reduced-size model of this wrap was constructed, a laser transmitter and signal source were mounted on top and a loose-tube fiber cable was installed in the model wrap. Tests of this arrangement showed that the predominant variation in detected total power went through minimums and maximums every 90 degrees of wrap physical rotation. (The variations measured were about 1% p-p, the level of polarization sensitivity of the photodiode in this setup.) It is believed that this is due to the physical rotation of the laser diode with respect to the photodiode. To first order, the laser and single-mode fiber act similar to a microwave circular waveguide transmission system transmitting linear polarization; that is, the transmitted polarization propagates down the fiber undisturbed. So, when the laser diode is physically rotated with respect to the photodiode, the fiber system reacts like a circular waveguide system when one uses a rotary joint to rotate the transmitted linear polarization and the detector is an imperfect circular polarizer. That is we're measuring the "axial ratio" of the photodiode detector. Of course, the fiber is not exactly like an ideal circular waveguide so it does act on the propagating wave's polarization, but this test indicates that effect is much less than the other, or at least is stable, if the cable movement is controlled in a reasonable fashion.

The GBT elevation wrap design is a simple flat loop (only 90 degrees of travel is required). A reduced-size model of this wrap was constructed, a laser transmitter and signal source were mounted on the swinging end and a loose-tube fiber cable was installed in the model wrap. Tests of this arrangement showed the effect to be much less than the magnitude of the photoreceiver polarization sensitivity, and its magnitude depended on the wrap bend radius. At a 3-foot bend radius, still less than that to be seen on the GBT elevation wrap, there was *no* total power variation with wrap position, although the sensitivity of our tests set the upper limit at about 0.01% p-p.

Both the VLBA and the Arecibo antennas' azimuth axis incorporate non-twisting cable wraps for sensitive IF and LO coax or fibers. This type of design should not physically rotate the laser diode with respect to the photodiode. We plan to confirm this by experiment. If it indeed works as expected, this should greatly reduce the azimuth dependency of the fiber system gain, and we will investigate the possibility of adding such a wrap for the analog fiber cable to the GBT azimuth axis.

These tests showed the importance of carefully controlling the fiber mechanical movements. The most difficult area to control is likely to be within the receiver room when the fiber leaves the loose-tube buffered cable and is interconnected with laser fiber pigtails. We will have to carefully engineer a system to mechanically protect and stabilize the fibers at this point.

Vibration Tests

There is concern about structural vibrations inducing gain modulation via the IF optical fibers. Some of the tests on the 140-foot hinted at this effect, but additional testing is needed to quantify and understand the problem. Some initial laboratory tests have been done which gave similar results for vibrations to a loose-tube buffered fiber and to a RG-9 coaxial cable, but further experimentation is needed.

Summary

We propose the following plan of action. Our goal will be to have most technical decisions made for a design approach by July, and by then to at least know with some confidence if our performance requirements are achievable. Assuming success in that, we would attempt to have at least one "production" IF channel constructed and ready to begin integrated tests by September, although with component lead time and limited engineering resources, that will be ambitious.

March:

- Make analytical decision on viability of the external modulator approach.
  - If viable, borrow or order evaluation unit with DFB laser.
  - If not viable, select and order one direct modulation DFB laser module and resume work on optical attenuator or other optical gain control element.

- Breadboard and test a non-twist azimuth wrap. If successful, begin studying feasibility of retrofit to GBT azimuth wrap.

- Quantify vibration sensitivity of optical fibers.

March/April:

- Identify "best available" photodiodes and begin procurement of 2 units. At the moment this appears to be in the New Focus product line.

- Make decision on continuum detector filterbank and order for two channels if appropriate.

April/May:

- Evaluate laser ALC and TC circuits and make "final" design decisions for laser control circuits.

May/June:

- Tests and circuit development of laser/modulators, control circuits, and characterize performance. Close an AGC loop and evaluate.

July/August:

- Make final packaging designs for Optical Driver modules, continuum detectors and filters, laser/modulators, and receiver modules. Rework M&C as necessary. Incorporate AGC, temperature control, and fiber management. Fab and assemble one or two IF channels.

- If appropriate, complete design of azimuth wrap retrofit.

Table 1
Photodiode Performance

Manufacturer	Detector	Bandwidth	Max Opt Power	Polarization Sensitivity		
	[module]	[GHz]	[mW]	[ΔV/V]pp	[σ]	[dB]
Ortel						
1990	2510A	3.0	2	0.0270	0.0038	-0.11887
1992	2510A	3.0	2	0.0069	0.0016	-0.03007
	2515A	10.0	2	0.0430	0.0047	-0.19088
	2516A	20.0	2	0.0304	0.0005	-0.13407
	2518A	15.0	15	0.0123	0.0034	-0.05375
Lasertron	QDMH2	10.0	2	0.0151	0.0009	-0.06608
New Focus	1414	25.0	2	0.0019	0.0009	-0.00826
	1434	25.0	10	0.0042	0.0037	-0.01828
	1514	6.0	2	0.0080		-0.03488
HP	HPDT0412	3.0	2	0.0057	0.0010	-0.02469

Table 2
Specification of PM Fibers

The extinction ratio of each individual connector was measured by Wave Optics. Mating connectors reduces the extinction ratio by approximately 4 dB. The last column is the estimated extinction ratio from the combined effects of the fiber and all the connectors.

Manufacturer	h parameter	Length	Connector	Fiber Extinction	Est. Total
	[1/meter]	[meter]	[dB]	[dB]	[dB]
3M	5 10^-5	10	29.3	33.01	25
			39.2		
		120	31.2	22.22	22
			35.4		
		222		19.55	20
Panda	1 10^-5	120	27.8	29.21	22
			25.8		
		222		26.54	27