Electro-Optical Technology Applied to Accelerator Beam Measurement and Control

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ABSTRACT

Recent improvements in optical components have provided another choice for signal processing for beam instrumentation and feedback. Signal transmission utilizing the low insertion loss of optical fibers has been attractive for years. Today optical amplifiers are available in several wavelength ranges. These amplifiers provide photon to photon gain, eliminating the need to down convert signals back to baseband for regenerative repeaters. New temperature stabilized fibers virtually eliminate transmission delay variation, a feature that can be critical for synchronizing distribution of timing signals. Optical attenuators, filters, couplers, and isolators are also readily available making signal processing similar to RF/Microwave engineering. The presentation will discuss these components and techniques while referring to a new optical storage ring that will be used to make a notch filter for Bunched Beam Cooling in the Fermilab Tevatron.

I. INTRODUCTION

Optical signal processing is now a viable alternative for implementing instrumentation in accelerators. Many of the new machines are either very large in size or very exacting in timing precision, old machines can also benefit from the improved performance of optical fibers and components.

Signal transmission around huge accelerators has typically been done with standard coaxial cable. Information bandwidth has increased over the years extending into gigahertz bandwidths. The long lengths coupled with wide bandwidth leads to high insertion loss and dispersion on standard coax. Single mode fiber optics and narrow line width lasers open up a new gateway to high data rates over long hauls with a minimum of loss and virtually no dispersion.

II. FIBER OPTICS VS COAXIAL TRANSMISSION LINES

A single mode optical fiber has a bandwidth capacity of 100 GHz per kilometer, far in excess of the modulators available today. The insertion loss ranges from 0.35 dB per kilometer at 1310 nanometers to 0.15 dB per kilometer at 1550 nanometers. There are two main types of fibers, the standard fiber has a zero dispersion wavelength of 1310 nanometers and dispersion shifted fiber with a zero at 1550 nanometers. The line width of the transmitter light source and its operating wavelength determine the maximum useful bandwidth transmission length product. Cost of signal mode fiber is approximately 25 to 50 cents per meter.

In contrast, coaxial cable must be chosen by examining the transmission bandwidth, allowable link loss, and available funds. Larger coax has lower loss, higher cost, and limited bandwidth due to higher mode propagation. Smaller coax has the advantage of increased bandwidth and lower cost, but at the expense of high losses. In all wide band use of coax, it is important to take into account the effects of dispersion. As can be seen in Figure 1, a length of 1/2 coax that is 100 feet long not only has a gain slope versus frequency, but also nonlinear phase characteristics due to dispersion.

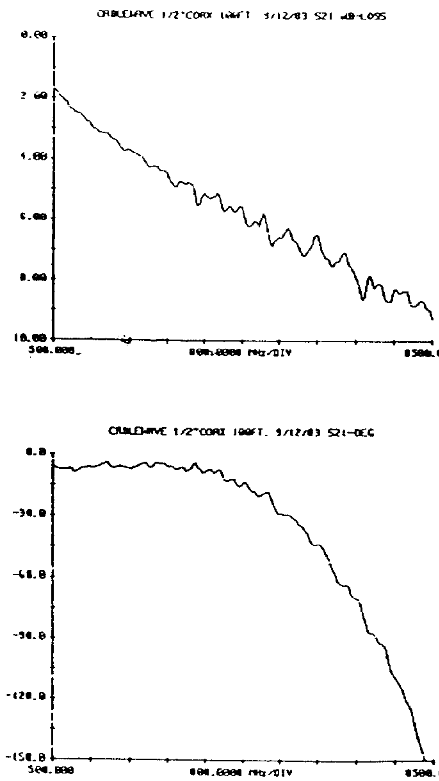

Figure 1. Amplitude and phase response for 100 feet of 1/2 in foam coax measured 0.5 to 8.5 GHz.

For very stringent timing conditions, a specially fabricated single mode fiber with very low temperature coefficient is available[1]. The fiber is jacketed in a special polymer coating that reduces the temperature dependent propagation characteristics dramatically while maintaining the low insertion loss and wide bandwidth characteristics of standard single mode fiber. Figure 2 shows the comparison of this special fiber and standard fiber versus temperature.

Most communication systems use amplitude modulation of the optical carrier for information transfer. Another possibility in some applications would require coherent signal transmission such as in interferometers. Due to polarization sensitivity, coherent systems rely on polarization maintaining

*Operated by the Universities Research Association under contract with the U.S. Department of Energy fibers and components. These fibers have elliptical cores which help preserve polarization. Couplers, polarizers and other components are available. [2]

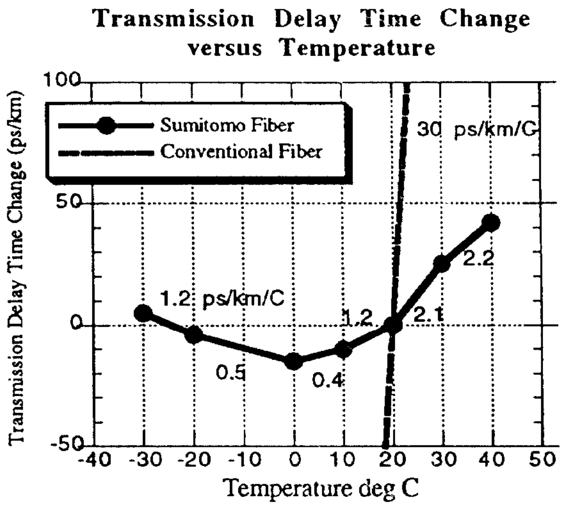

Figure 2. Transmission delay time change versus temperature for conventional and temperature stabilized single mode fiber optic

III. COMPONENTS

Instrumentation in the RF/Microwave frequency ranges has always required more than just a good transmission medium. Other components such as couplers/splitters, isolators, filters, switches, attenuators, transmitters, receivers, amplifiers, etc. are necessary. All of the above devices are now available in fiber optic form.

Fiber optic couplers/splitters are available over a wide range of coupling values. The advantage over their microwave counter parts is that the directivity of these components routinely exceeds 60 dB. Fanout splitters with 2 to 16 outputs are catalog items.

Isolators utilizing the faraday rotation of the light rays can provide 40 plus dB of reverse isolation. This is an important consideration in conjunction with laser transmitters. A laser transmitter outfitted with an isolator can afford a higher percentage of output coupled light with out fear of back reflections that might otherwise damage the laser. The end result being higher transmitter power and longer transmission length capability.

Manually and voltage tuned Fabry-Perot bandpass filters are available. They are typically used for separating different wavelength carriers in wavelength division multiplexing systems. Band limiting noise is also a use with optical amplifiers.

Programmable MxN switch matrices with switching times typically 15 ms or less are standard. Most switches have back reflections of 55 dB typical. Attenuators with continuous tuning range of 30 dB are available in manual and voltage tuned versions.

The bandwidth of transmitters and receivers has increased steadily over the last few years. Transmitter bandwidths of 15 GHz employing amplitude modulation of laser diode current are standard. Receiver bandwidths exceed 20 GHz. Due to the low input impedance of the laser and photo diodes, resistive matching networks are used to achieve the broad bandwidths. Lossy matching yields a typical insertion loss of 40 dB, but is flat across the band as shown in figure 3. [3] If a bandwidth greater than 15 GHz is necessary, external Mach-Zender interferometer modulators are capable of bandwidths in excess of 20 GHz.[4]

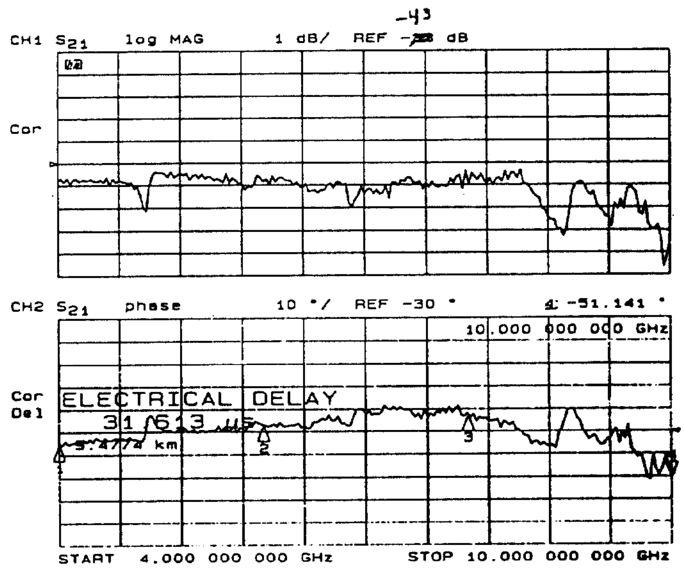

Figure 3. Broad band optical link with 6.44 km of fiber measured from 4-10 GHz.

Perhaps the most important innovation of the last decade is the optical amplifier. Long transmission links such as the trans- Atlantic fiber required electronic repeaters every 40 to 60 kilometers. This meant decoding and re-modulating the signal some 125 times. With an optical amplifier, the information never leaves the photon domain. There are two types of optical amplifiers, a solid state version which operates at 1310 nm, and an Erbium doped fiber version which operates at 1550 nm.

The solid state amplifier (SOA) [5] is basically a diode laser biased below the critical current The reflective facets are replaced with anti reflective coatings. Incoming photons stimulate emission in the diode amplifier producing 10 to 15 dB of bi-directional gain. The draw back of these amplifiers is the high broad band noise output. They typically are used with some type of bandpass filter.

Erbium doped fiber amplifiers (EDFA) [6] are lengths of rare earth single mode fiber that are pumped with a diode laser of a different wavelength. The pumping causes a population inversion that releases stimulated emission from incoming photons. These amplifiers are substantially quieter than the solid state units and are capable of more gain and output power. This coupled with the lower insertion loss of fiber at 1550 nm has allowed transmission links that require repeaters at intervals of 200 km. The trans-Pacific link will be installed with Erbium amplifier technology.

For now, finding the rare earth that will make a fiber amplifier at 1310 is still a research project. Most of the installed fiber systems operate at 1310 nm so there is keen interest in fiber amplifiers at this wavelength.

IV. EXAMPLE OF OPTICAL SIGNAL PROCESSING

One example of signal processing using many of the mentioned components is a special correlator notch filter that is required for Bunched Beam Stochastic Betatron Cooling in the Fermilab Tevatron[7][8]. This filter is designed to provide a recursive notch filter operating 4-8 GHz that has a "brick wall" amplitude transfer function with flat phase between notches, see figure 4. The filter is designed to reduce the longitudinal spectral lines from the bunched beam signal (figure 5) with out degrading the amplitude and phase of the betatron schottky signal sidebands. Notch frequency stability of 0.1 part per million is desired.

A simplified block diagram of the filter is shown in figure 6. If the optical storage ring can be built to have unity gain, the Q becomes infinite, thus leading to the desired brick wall transfer function. [9] As was pointed out earlier, optical fiber has very low insertion loss, but not zero. In addition, there is insertion loss in the input and output couplers. The length of fiber used to make this filter is 4.5 kilometers in length which corresponds to a transmission signal delay of 21 microseconds, i.e. the revolution time of the beam in the Tevatron. The insertion loss of the optical fiber alone is 2 dB.

Our filter uses the Sumitomo temperature stabilized fiber to achieve the frequency stability mentioned earlier. Figure 7 shows the storage ring Q as a function of optical loop gain.

Before the availability of optical amplifiers, such rings were made by putting a repeater within the loop thus requiring demodulation and regeneration. At wide microwave frequencies this presents a degradation in signal to noise ratio. The solid state optical amplifier used in this filter is polarization insensitive , an important requirement. The slightest twist of any part of the fiber causes the polarization to change dramatically. If the loop gain is not maintained close to unity, the filter will have low Q. If the gain exceeds unity, you have an optical oscillator on you hands that could damage the amplifier.

Due to the high output noise of the amplifier, a tunable bandpass filter is placed after the amplifier. The amplifier has gain in both directions and the laser transmitter is sensitive to back reflections. An isolator is installed to reduce reverse loop gain.

The dynamic range of the optical transmitter/receiver is 55 to 60 dB. This is insufficient dynamic range for this filter application hence a parallel microwave path provides the short leg of the correlator filter. The spectral width of the laser transmitter source is of importance with such long delays. To avoid any coherence length problems, one would like a wide spectral source. Distributed feedback lasers[10] produce very narrow line widths that can lead to carrier interference in the loop. We are using a Fabry-Perot laser which has a line width of 10 MHz.

Figure 8 is a gain and phase plot of the actual filter performance. Narrower frequency span data shows the notch depth to be in excess of 30 dB. Figure 9 shows the dynamic range of the filter.

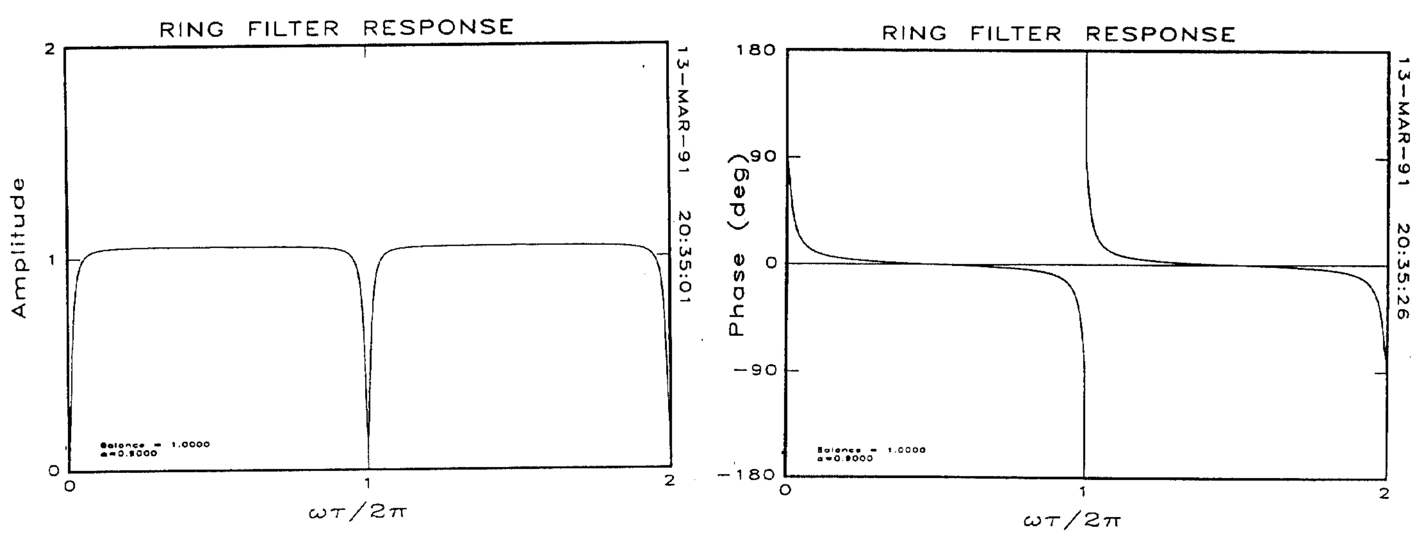

Figure 4. Ideal amplitude and phase characteristics for a storage ring correlator notch filter.

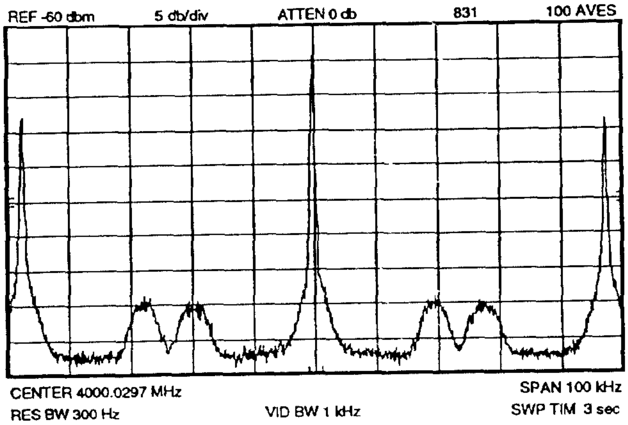

Figure 5. Typical Tevatron vertical bunched beam spectrum at 4 GHz as measured by the vertical proton pickup.

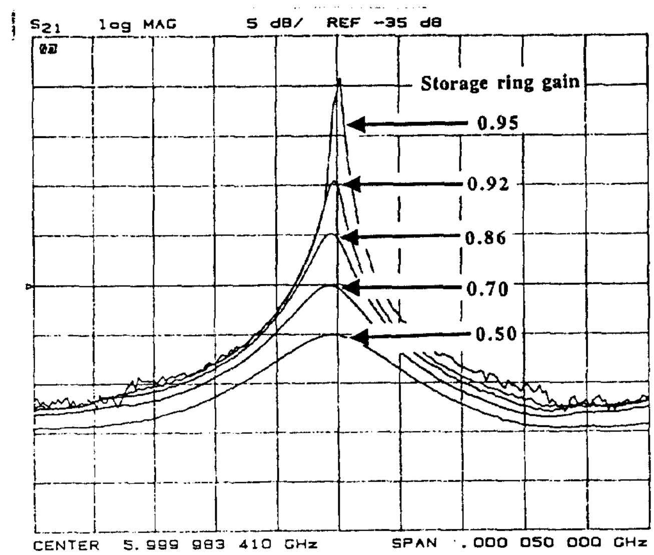

Figure 7. Variation of optical storage ring Q as a function of loop gain.

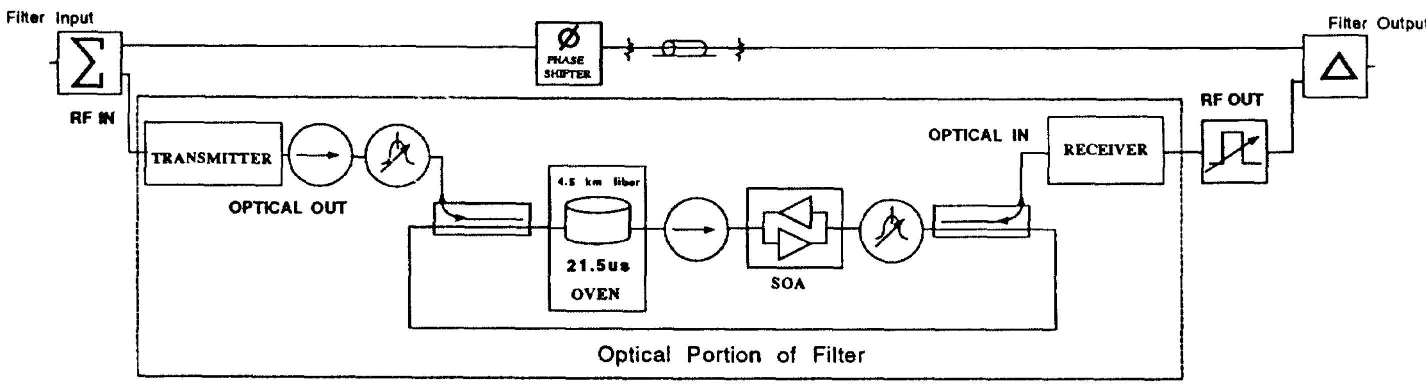

Figure 6. Block diagram of optical storage ring correlator notch filter

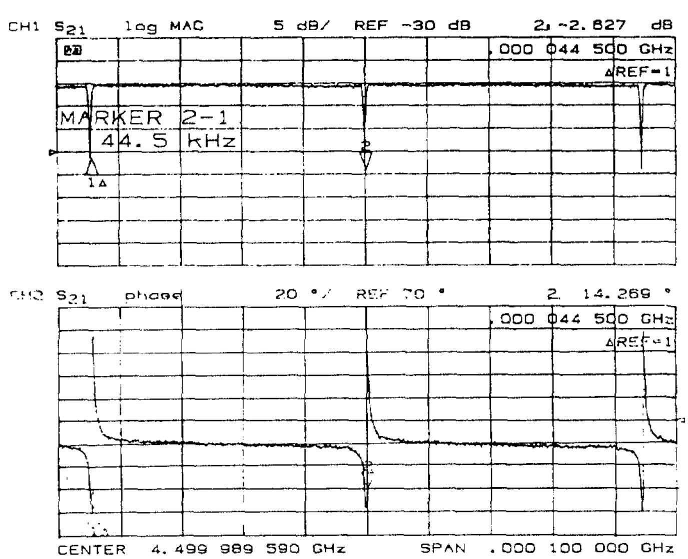

Figure 8. Amplitude and Phase plot of actual filter performance.

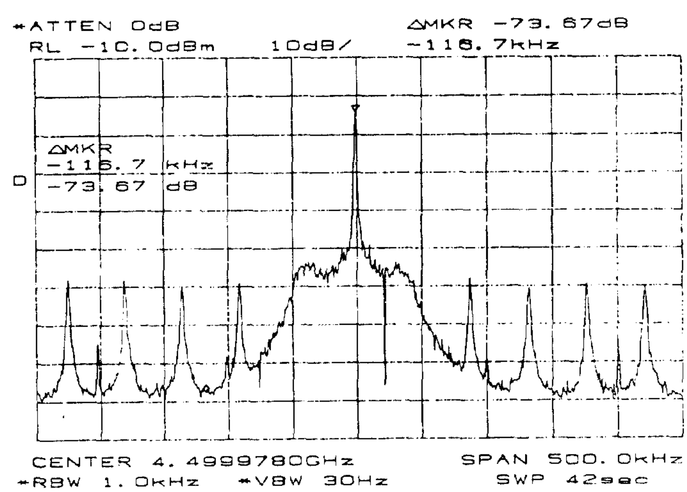

Figure 9. Dynamic range performance of actual filter. Filter is narrow band swept by network analyzer and plotted on wide band with spectrum analyzer. Peaks are noise floor of optical portion of correlator filter.

V. CONCLUSIONS

We have successfully used optics to create a filter for a feedback system that could only be fabricated in the optical domain because of the limitation of microwave transmission lines and devices. Four such filters must be fabricated for the full Tevatron Bunched Beam Stochastic Cooling systems. Future plans are to extend the cooling bandwidth to 8-16 GHz. Because of the wide bandwidth capacity of the fiber optics, only the transmitter and receiver will need to be replaced.

VI. ACKNOWLEDGMENTS

I would like to thank Gerry Jackson for his efforts of doing the theoretical calculations associated with the filter design and Ernie Buchanan for his diligent handiwork in filter construction. He has spent many hours with strands of the angel hair fibers.

VII. REFERENCES

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