Fermi National Accelerator Laboratory

FERMILAB-Conf-92/290

Optical Signal Acquisition and Processing in Future Accelerator Diagnostics

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October 1992

Proceedings of *3rd International Workshop on Advanced Accelerator Concepts* ,
Port Jefferson, Long Island, New York, June 14-20, 1992

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ABSTRACT

Beam detectors such as striplines and wall current monitors rely on matched electrical networks to transmit and process beam information. Frequency bandwidth, noise immunity, reflections, and signal to noise ratio are considerations that require compromises limiting the quality of the measurement. Recent advances in fiber optics related technologies have made it possible to acquire and process beam signals in the optical domain. This paper describes recent developments in the application of these technologies to accelerator beam diagnostics. The design and construction of an optical notch filter used for a stochastic cooling system is used as an example. Conceptual ideas for future beam detectors are also presented.

BEAM DIAGNOSTIC CONSIDERATIONS

When beam detectors based on coupling to beam generated electric or magnetic fields or vacuum pipe image currents are designed, a number of important decisions must be made. This is especially true with wide frequency bandwidth devices such as beam position monitors[1], Schottky noise detectors[2], and resistive wall monitors[3].

The physical shape of the detector is similar to that of an antenna, detecting some fraction of the frequency spectrum of the beam charge induced fields. The impedance spectrum of the detector determines the signal level and distortion of this signal. Thermal and external electrical noise are considerations which are also included into the design.

Once the signal is acquired, it must be transmitted (usually to a location which is generally inhabitable by humans during beam operations) and processed. Transmission lines suffer from dispersion, attenuation, and multimoding. Dispersion is due to the dielectric material which forms the insulation between the two conductors of the TEM transmission line. The attenuation per unit length of cable is inversely proportional to the surface area of the conductors and increases with frequency, until in the microwave regime one can loose up to 200 dB/km. Multimoding occurs at frequencies at which the distance between the transmission line conductors is approximately a half wavelength. In order to prevent multimoding as higher frequencies are required, physically smaller diameter cables are used, with a correspondingly larger attenuation per unit length.

OPTICAL SIGNAL TRANSMISSION

There are generally two reasons why fiber optic communication of signals is chosen over electrical means. First, there are environments where high voltages and/or large ground current fluctuations make electrical signal transmission hazardous or noisy. Second, because of the very long attenuation length and low dispersion of present glass fibers, long optical transmission and delay lines provide unparalleled performance.

Basic Optical Transmission Schemes

There are presently two basic methods for transmitting signals via optical transmission lines. In the first, the output power of the laser diode is modulated by the signal of interest. Second, an optical modulator after a constant laser source is used to modulate the power. In both cases a photodiode converts power back to electrical current.

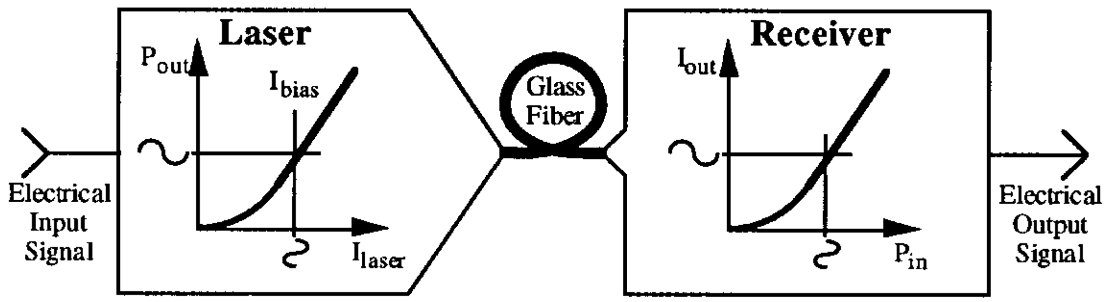

Figure 1: Sketch of an optical signal transmission system in which the laser diode output power is modulated by an input current carrying the signal of interest. Note that the laser chip must provide a bias current to insure linear signal conversion. A photodiode is used to convert the laser power modulation back into an electrical signal.

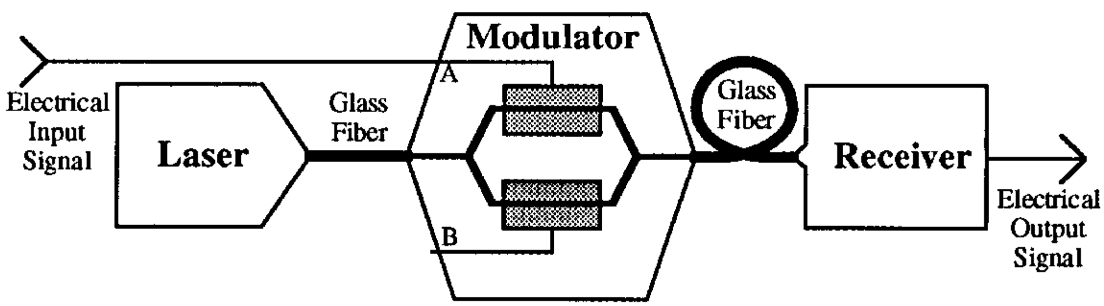

Figure 2: Sketch of an optical signal transmission system in which the constant power from a laser diode is modulated by an external signal. The modulator works by electrically modifying the optical length of a material, such as $LiNbO_3$, through which half of the light traverses, thus inducing partial destructive interference when the light from the two paths is again superimposed.

Figure 1 is a sketch of a standard system in which the laser power is directly modulated[4]. Capable of amplitude modulating the power of the laser in the frequency range of DC to 12 GHz, the vast majority of instrumentation needs are serviced by this type of system. With an attenuation of approximately 0.3 dB/km and negligible dispersion (both due to the doping of the glass and the fact that the carrier frequency of the light is approximately 300 Terahertz), transmissions over very long distances are possible with no signal degradation. The disadvantage of this scheme is the insertion loss of approximately 40 dB (due to the low input impedance of laser diodes and the need to terminate the input signal into 50 Ω), which means high levels of preamplification are needed to avoid signal-to-noise degradations.

In order to attain higher modulation frequencies, it is necessary to use optical modulator technology[5]. In a modulator, the light from an optical fiber is directed into an optical silicon optical channel, where the light is split equally into two separate paths. The two beams are then sent through a material, such as $LiNbO_3$, where the optical length of the path is proportional to the voltage applied across it. The two light signals are then recombined and launched into the output fiber. If the length of both paths are changed together, the output light wave is phase modulated. This is useful in cases where interferometry is being performed in some other part of the optical circuit.

Of more direct interest to instrumentation designers is the mode in which the path length in the two legs are oppositely modified (or in most cases where output phase is not important, just one leg). In this case the power in the output fiber is modulated through partial destructive interference. This technique is actually used in some accelerator RF systems and is called paraphasing[6]. Because of the small size of the modulating material, the capacitance of the electrical junction across it is very small. Therefore, modulation frequencies up to 20 GHz are already available on the market. As apposed to the input to a laser diode, the input impedance of a modulator is very high.

Two applications of optical signal transmission at Fermilab are good examples of the utility of this technology. First, optical signal transmission is used to make impedance measurements of an RF cavity. In the second, fiber optics may be used to transmit Schottky signals across the chord of an accelerator for stochastic cooling.

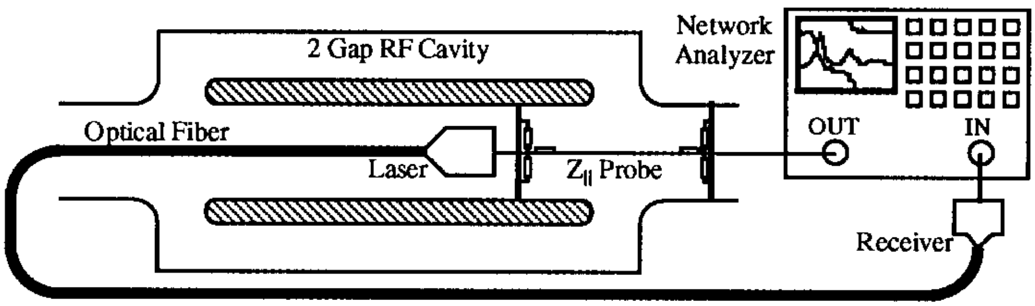

Figure 3: An elegant example of the range of uses for optical fibers in signal transmissions. In order to measure the longitudinal (or even transverse if the wire is moved radially) impedance of a single gap, the signal wire through the other gap would normally invalidate the measurement.

In the first case, because of the fact that most Fermilab RF cavities are of the two gap resonant transmission line variety, where the two gaps are separated by roughly half an RF period, impedance measurements pulling a single wire down the entire length of the cavity can be very confusing[7]. Therefore, it is desirable to measure the impedance of a single gap, and then derive the double gap response independently. The problem is that any S_{21} measurement across an accelerating gap requires a signal cable to cross the other gap, partially shorting it and affecting the measurement. The solution is to transmit the S_{21} response via optical fiber back to the input of the network analyzer[8]. Figure 3 contains a sketch of this solution.

In damper systems, in which measured betatron displacements are corrected by a kicker placed an odd number of 90° downstream, beam position information acquired at the pickup must be transmitted to the kicker in time with the beam. Since the signal in an optical fiber propagates at approximately 2/3 the speed of light, it is not possible to send that signal through the link ahead of a relativistic beam by transmitting along the diameter of a circular accelerator. But, as shown in figure 4, other chords in a wide variety of accelerator shapes are possible.

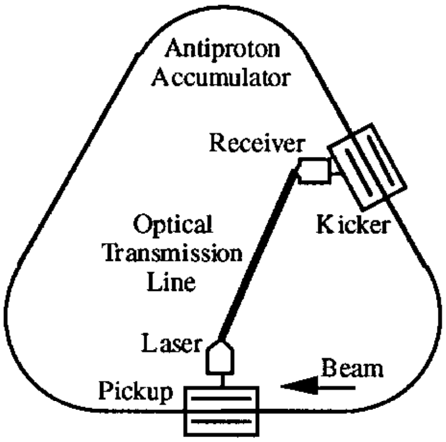

Figure 4: Sketch of a optical transmission system for a stochastic cooling system. In principle, any damper like system where the phase advance between the pickup and the kicker is an odd multiple of 90° could be configured in a similar manner.

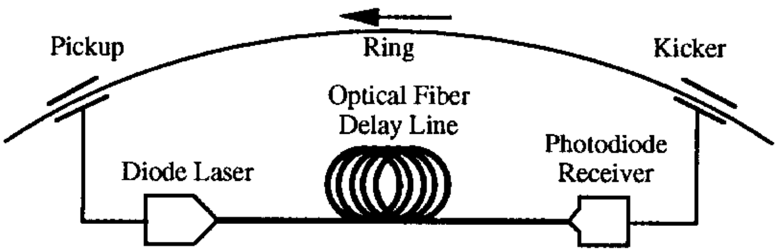

Figure 5: Rough sketch of a damping system where the one turn delay between the pickup and kicker is provided by an optical fiber delay line. In order to suppress beam oscillations or stochastically cool beam, there must be an odd number of quarter wavelengths of phase advance between the pickup and kicker around the ring.

Optical Delay Lines

Designers of RF, stochastic cooling, and feedback systems often need to delay a beam signal for one accelerator revolution in order to correct the beam energy or angle. Stochastic cooling systems often need repetitive notch filters designed to notch or phase shift the beam signal at the revolution harmonics. In both cases, an optical delay line is very useful, especially for accelerators with radii that of the Fermilab Tevatron and beyond.

Figure 5 contains a sketch of a delay line used at Fermilab in the bunched beam stochastic cooling system in the Tevatron[9]. Especially useful in accelerators systems for which cutting a chord across the ring is not a viable option (for instance, at Fermilab the center of the Main Ring and Tevatron is composed of Federally protected wetlands and a very popular prairie grass reclamation project), the pickup and kicker are separated by the machine tune minus enough phase advance to provide an odd number of quarter wavelengths within the feedback loop.

Repetitive Notch Filters

A transverse feedback system whose purpose is to damp injection oscillations, stochastically cool beams, or suppress instabilities often suffers from either power limitations or excessive dynamic range requirements due to power at revolution frequency harmonics caused by the beam passing off-center through the pickup. In order to avoid the first problem, one typically chooses a high power amplifier to drive the kicker that has no DC response. In this way the feedback system will not act as a steering magnet. Though this solution works well in most applications, it can be quite a problem for systems that require bunch-to-bunch isolation. For instance, if a positive kick to a single member of a set of bunches is required, the other bunches receive a negative kick so as to guarantee zero area under the net waveform (as required by a lack of DC response). This residual kick is a source of noise which will eventually cause emittance growth in hadron beams.

Another solution which prevents both the first and second concerns is to suppress the power in the revolution harmonics just after the pickup, before the rest of the system electronics, by means of a repetitive notch filter. Sketched in figure 6, this filter is generated by subtracting from the pickup signal the signal from the previous turn.

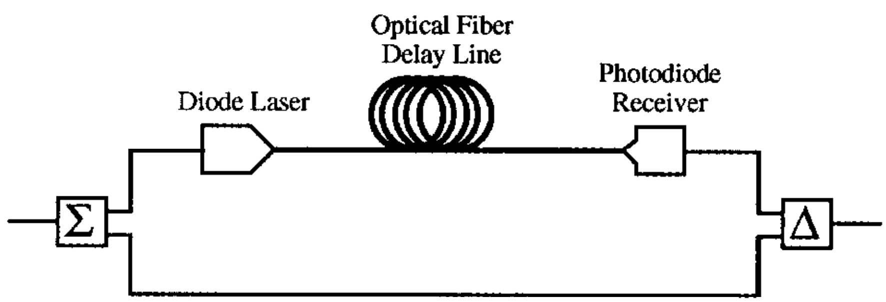

Figure 6: Example of a repetitive notch filter in which an optical fiber is used to generate a very long delay required in large radius accelerators.

The frequency response of such a filter is shown in figures 7 and 8. In the time domain, if both signals are perfectly matched in amplitude and time, the signal net output signal of the filter given a sinusoidal input would be

$$V(t) = V_0 e^{i\omega t}\left(1 - e^{-i\omega\tau}\right) \qquad , \qquad (1)$$

where τ is the delay of one leg with respect to the other. In the frequency domain this equation becomes

$$V(\omega) = [1 - \cos(\omega\tau)] + i\sin(\omega\tau) \qquad , \qquad (2)$$

where the real and imaginary parts have been separated. The amplitude and phase of this filter are

$$A(\omega) = \left|\sqrt{2}\sin\left(\frac{\omega\tau}{2}\right)\right| \qquad , \qquad (3)$$

$$\phi(\omega) = \arctan\left[\frac{\sin(\omega\tau)}{1 - \cos(\omega\tau)}\right] \qquad . \qquad (4)$$

As can be seen from the figures, this type of filter has amplitude notches at all frequencies where the delay is exactly one wavelength. In an accelerator, if the delay is exactly one turn every harmonic of the revolution frequency is suppressed. The problem with this type of filter is the slew of the phase response in the passbands. In bunched beam stochastic cooling systems, where the betatron power is occupying half or more of the passband, those particles in the frequency regime beyond 45° are heated instead of cooled.

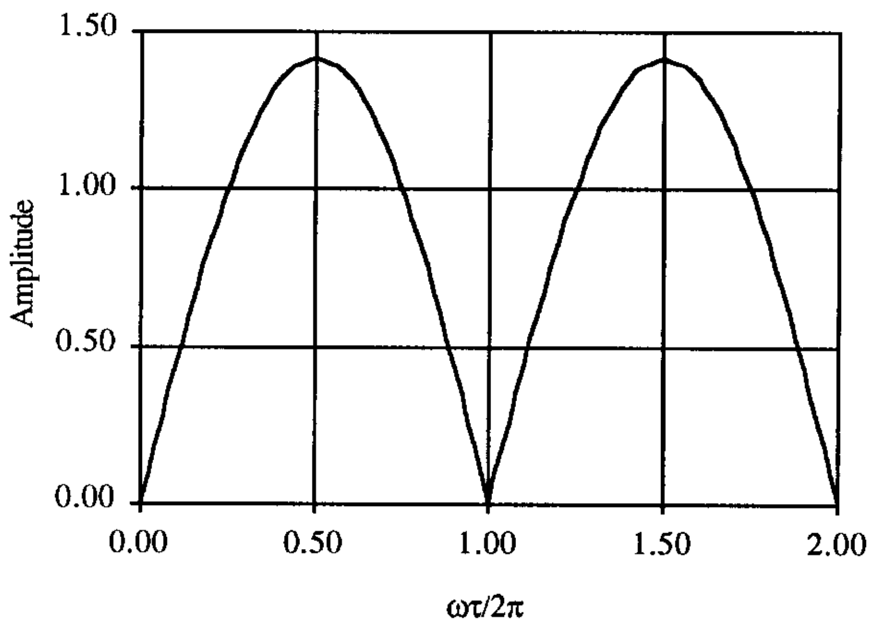

Figure 7: Amplitude response of a one-turn delay repetitive notch filter.

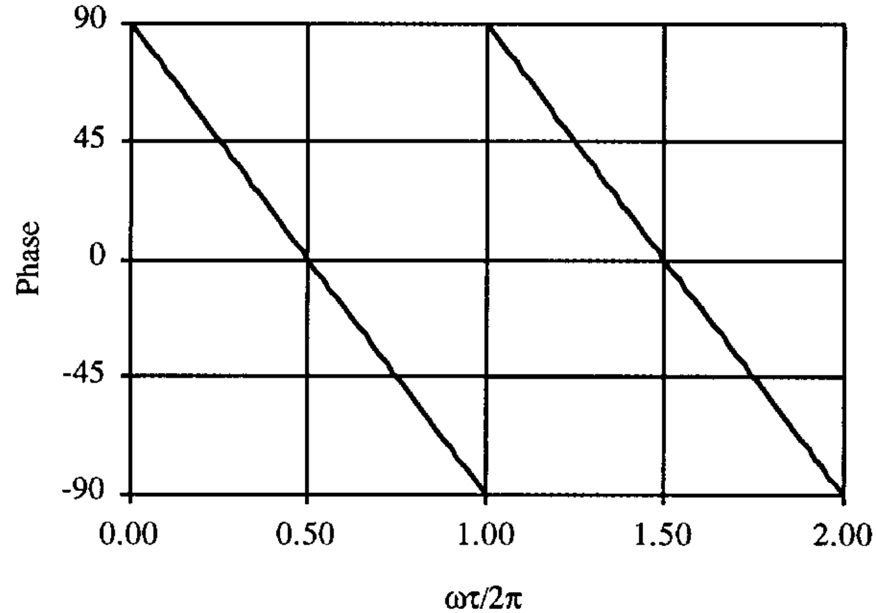

Figure 8: Phase response of a one-turn delay repetitive notch filter.

PHOTON STORAGE RINGS

The technology of optical fibers has quickly moved to provide optical components normally found in the RF and microwave worlds. Devices like directional couplers, attenuators, amplifiers, circulators, and isolators are now all available. With these components it is possible to produce filters and instruments not found in the electrical domain. By far the most powerful fiber geometry found so far for instrumentation and feedback purposes is the fiber optical loop, or photon storage ring.

Loop Notch Filter

In order to reduce the phase slew in the one-turn delay repetitive notch filter, an optical storage ring can be used to subtract the exponential average of all previous turns from the present turn. A sketch of the filter is in figure 9.

The directional couplers transmit some of the light from one path into the other available path in the same direction. Therefore, in the left directional coupler in figure 9, the beam signal launched by the laser is partially inserted into the fiber storage ring in the clockwise direction. The coupling can range anywhere from 3dB to 40 dB, the same range found typically in RF and microwave devices. The difference in the optical domain is that the coupling is exactly uniform over multi-GHz bandwidths, whereas electrical devices have phase and amplitude ripple in their passband which destroy the response of the electrical filters of this type.

Optical amplifiers are the technological breakthrough which really make this filter extraordinary[10]. By directly multiplying photons without the intermediate transformation to electrical current amplification, low nose amplification of the modulated laser power is possible. Gains of up to 40 dB have been attained. There are at present three available technologies: modified silicon laser chips, erbium doped fiber amplifiers, and nonlinear crystal multiplication. The first two are based on the excitation of a metastable state by a pumped source, and generate noise due to the amplification of spontaneous emission of the metastable state before it could be deexcited by stimulated emission. Fortunately, the noise power is spread over Terahertz of bandwidth which is easily removed by an optical bandpass filter. Silicon chip amplifiers are simply diode lasers with the reflecting mirrors at either end of the optical cavity removed. The metastable state is excited by direct electrical stimulation. Erbium doped fibers are pumped with a high power laser of a specific wavelength which excites the required metastable level. At present at Fermilab the silicon amplifier is used, though erbium doped fiber amplifiers are going to be used in the near future.

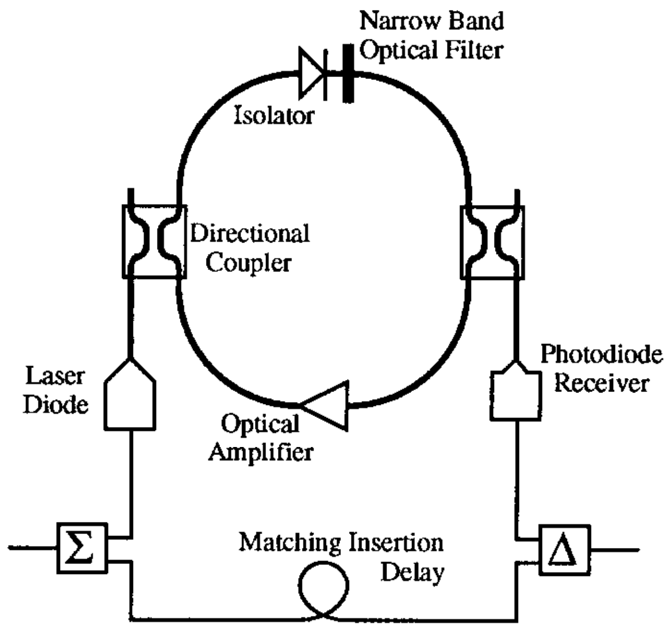

Figure 9: Sketch of a loop notch filter which is being built for the Tevatron bunched beam stochastic cooling system.

The signal in the optical storage ring can be written in the time domain as

$$V(t) = V_0 e^{i\omega t} \sum_{n=1}^{\infty} \alpha^n e^{-in\omega\tau} \quad , \tag{5}$$

were α is the fraction of an inserted signal which survives exactly one turn in the optical storage ring. To write the voltage in the frequency domain, the equality

$$\sum_{n=1}^{\infty} x^n = \frac{x}{1-x} \tag{6}$$

must be employed. Therefore, the voltage in the storage ring in the frequency domain is

$$V(\omega) = V_0 \frac{\alpha e^{-i\omega\tau}}{1-\alpha e^{-i\omega\tau}} \quad . \tag{7}$$

At the revolution frequency harmonics the exponential factor is unity. Therefore, the gain at these frequencies is $\alpha/(1-\alpha)$. In the full filter, the subtraction needs to be amplitude balanced such that the revolution harmonics are reduced to zero. Therefore, the response of the entire filter is

$$V(\omega) = V_0 \left(1 - \frac{1-\alpha}{\alpha} \frac{\alpha e^{-i\omega\tau}}{1-\alpha e^{-i\omega\tau}} \right) \quad . \tag{8}$$

By reworking this equation, the compact form

$$V(\omega) = V_0 \frac{1-e^{-i\omega\tau}}{1-\alpha e^{-i\omega\tau}} \tag{9}$$

is attained. Finally, the equation can be written with the real and imaginary parts explicitly separated as

$$V(\omega) = V_0 \frac{[(1+\alpha)(1-\cos(\omega\tau))] + i[(1-\alpha)\sin(\omega\tau)]}{1-\alpha\cos(\omega\tau)+\alpha^2} \quad . \tag{10}$$

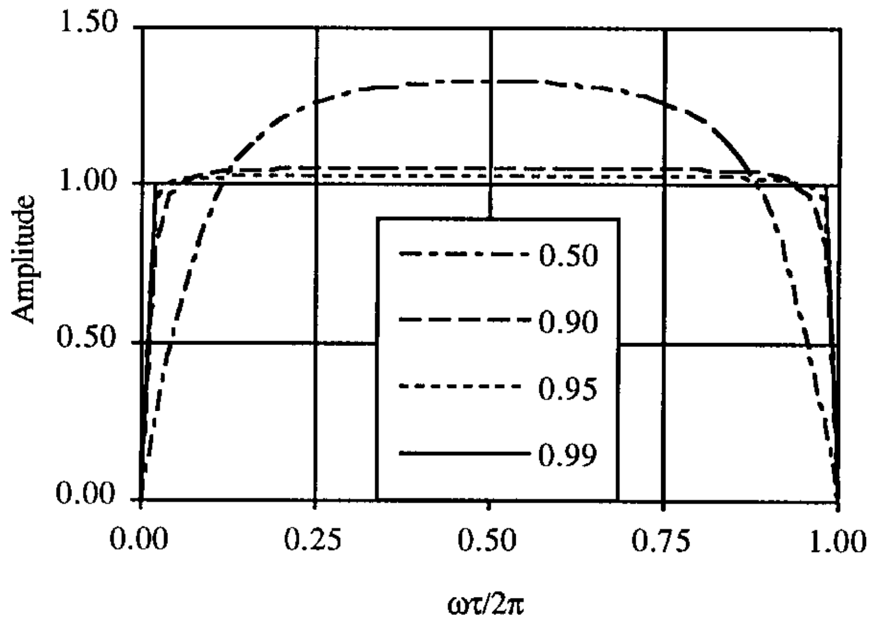

Figure 10: Amplitude response of a loop repetitive notch filter. The curve for a=0.99 is almost indistinguishable from the value of unity, except for the sharp drops to zero at harmonics of the revolution frequency.

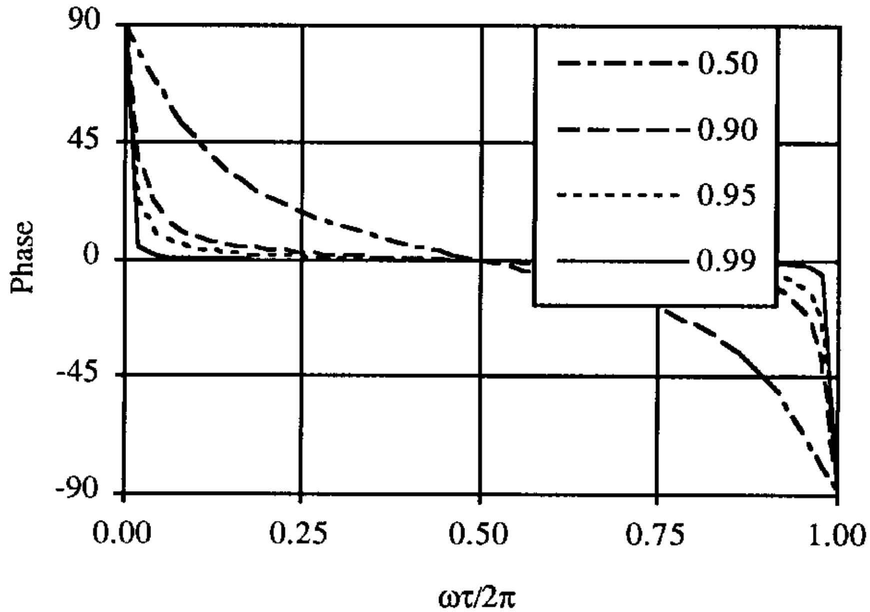

Figure 11: Phase response of a loop repetitive notch filter.

Figures 10 and 11 contain plots of the amplitude and phase of this filter as a function of frequency and the amplitude survival factor α. Note that the response of the filter becomes more like an infinite impulse repetitive notch filter as α goes to unity. The reason for this effect is the fact that the loop filter is acting as an exponential filter with a 1/e length of $1/(1-\alpha)$ turns of the loop. Therefore, the signal coupled out of the loop is closer to zero for all non-revolution harmonic frequencies as the averaging gets longer and the filter output is simply the prompt input. In the time domain, when thinking about bunch signals from a beam position detector, the loop filter subtracts the average bunch profile signal (devoid of betatron oscillation induced amplitude modulation) from the prompt signal, therefore subtracting out the closed orbit offset portion of the beam signal without inserting delayed betatron information at the wrong phase (which shows up as the phase slew in the filter response).

Real Time Bunch Length Monitor

An ingenious idea for creating a real time bunch length monitor for an electron beam, created at CERN by Claude Bovet, is also based on a photon storage ring[11]. Shown in figure 12, the basic idea is to generate a histogram with a width proportional to the bunch length by sampling injected synchrotron radiation photons with a fast risetime photodiode sensitive to single photons.

If coupling in and out of the loop is sufficiently small, on average less than one photon per ring revolution is registered at the photodiode. Since the temporal distribution of registered photons comes from the parent distribution of the incident synchrotron radiation, the time spread of photon arrivals is equal to the bunch length. If the circumference of the optical storage ring is much smaller than the spacing of bunches (or the accelerator circumference if bunch gating is employed) real time bunch length monitoring is possible.

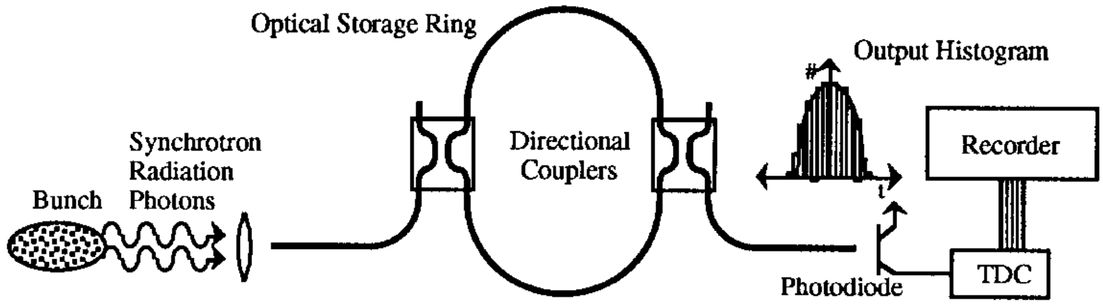

Figure 12: Sketch of a real time bunch length monitor based on a photon storage ring.

Signal Shaping

In many beam signal processing applications the best available technique requires repetitive signals (i.e. are frequency domain based). An excellent example is the AM-PM conversion technique[12] used in many beam position monitoring systems in the world. Unfortunately, sometimes the stimulus for such systems is a single bunch, which acts as an impulse and invalidates the meaning of the processing result.

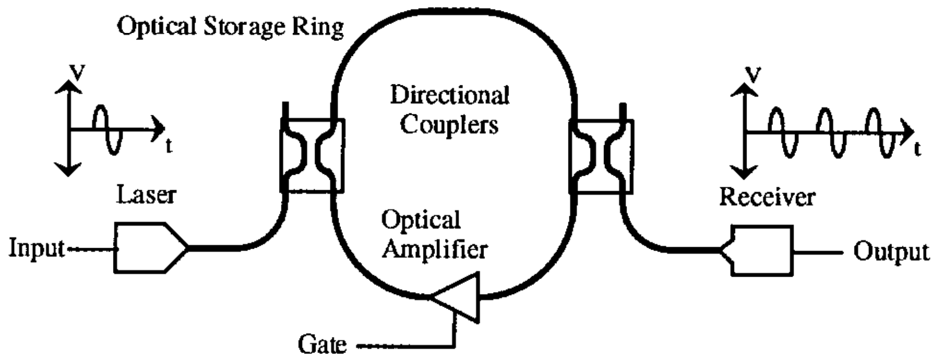

Figure 13: Example of a signal repeater used to make a transient beam signal suitable for processing using an inherently frequency domain method.

There are a number of ways to try to convert an impulse into a signal suitable for frequency domain processing techniques. A very powerful means is to repeat the impulse signal at a regular interval. This can be accomplished by either placing an array of evenly space detectors in the tunnel[13], or repeating the impulse from a single detector by sending the signal into a unity gain loop (see figure 13). Even though in principle electrical signal loops could be used to create repetitive signals, the noise and signal quality features of optical systems makes this a preferred technological platform, especially in large accelerators or those with very low processing frequencies.

OPTICAL DEVICES IN BEAM DETECTORS

Work is just now starting at Fermilab investigating the use of optical components inside electromagnetic beam detectors for direct conversion to optical signal transmission and processing. Especially in the case of wide bandwidth detectors, optical fiber components built into electromagnetic detectors will become a necessity.

Present design concepts fall into two categories. In the first, since the beam acts as a current source and the input impedance of laser diode chips are relatively low, the use of lasers inside low impedance devices such a resistive wall monitors becomes attractive. On the other hand, in pickups which have fixed impedances, local terminations coupled with high input impedance modulators may be the preferred signal encoding method.

In the case of a resistive wall monitor[14] the design goal is to shunt the image currents of the beams through a set of resistors, instead of around the resistors on the inside surface of it's metallic containment vessel. This is accomplished by increasing the inductance of the containment vessel path, raising the impedance to a value much greater than the net resistance across the ceramic beam pipe gap in the frequency range of interest. The present generation of monitors of this type at Fermilab have a useful bandwidth from 3 kHz to 6 GHz. Figure 14 is a sketch of the arrangement of 50Ω resistors crossing over the ceramic gap. The black resistors are replaced by 50Ω cables which are combined to generate a transverse position insensitive response.

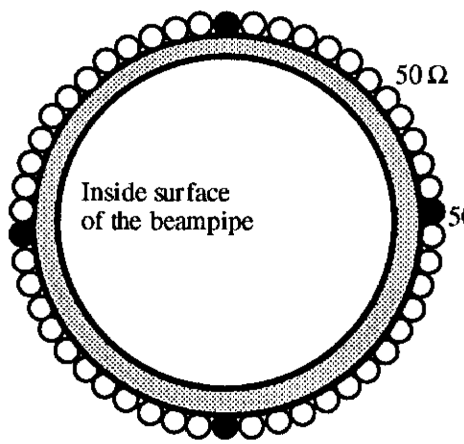

Figure 14: Sketch of an electrically based resistive wall monitor in which 4 50Ω resistors are replaced by 50Ω signal cables which are combined to create a transverse beam position insensitive current monitor.

Clearly, the above detector throws away about 48/52 of the signal, which is dissipated in the non-instrumented resistors. If the resistors were replaced by laser diodes which were all linked together, a 12 GHz bandwidth detector with much less high-μ material needed to generate the required inductance could be produced. In fact, such a device could be built without a ceramic gap, as shown in figure 15, and may be capable of producing better signal-to-noise ratios.

It is also possible to use the high input impedance of optical modulators to encode beam information onto the power from a laser. An excellent example is that of a Schottky detector in which each detector pad is terminated into it's characteristic impedance[15]. Shown in figure 16, beam pickups (directional couplers) of typically

100 Ω transmit signals along 100 Ω transmission lines to properly terminated modulator inputs. Because the propagation velocity in optical fiber is 2/3 the speed of light, the delay between the pickup and the modulator must be increased per stage. The benefit of such an array of pickups is that though the noise power increases linearly with the number of pickups, the signal power goes as the square. Since no impedance matching networks are required to recombine the signal, the deleterious effects stemming from the recombination of slightly different signals (due to misalignment of the array with respect to the beam trajectory) are completely avoided.

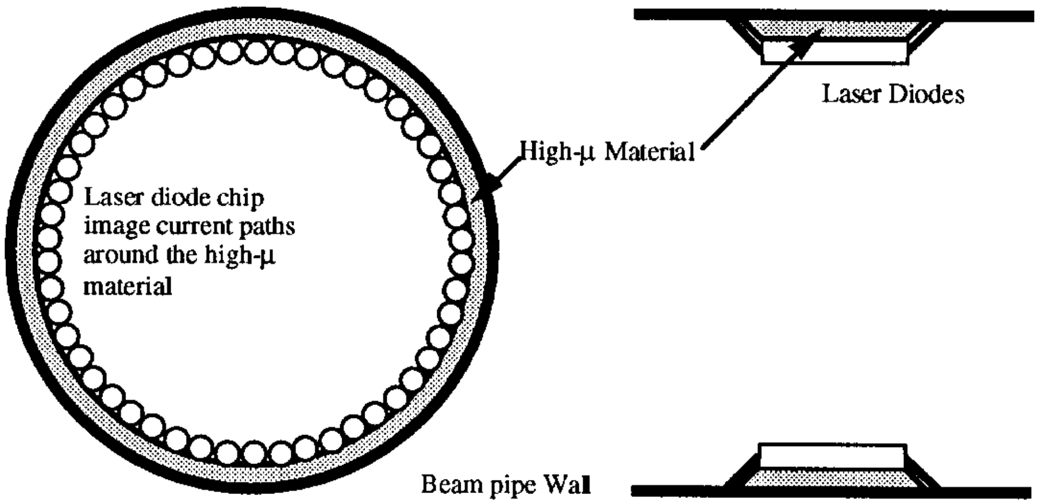

Figure 15: Sketch of another resistive wall monitor in which the laser diodes shunt the image current inside of the high permitivity material through the lasers and modulating the laser power.

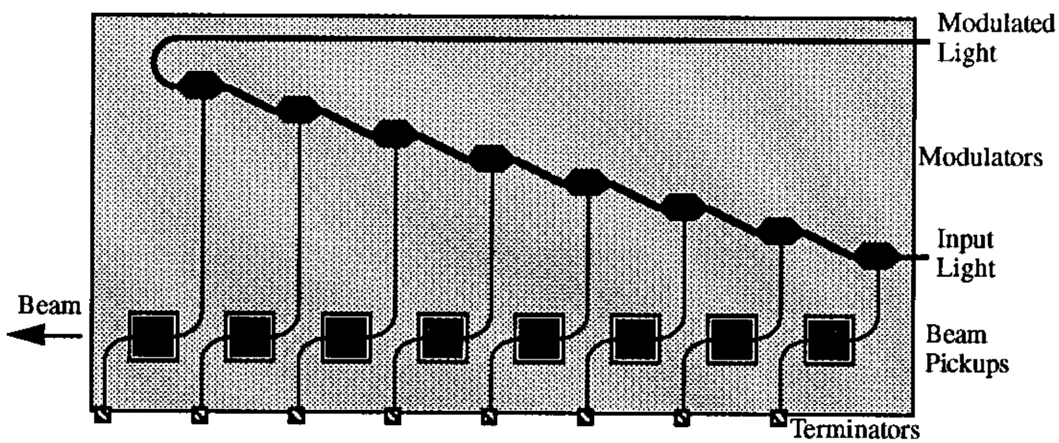

Figure 16: Example of the use of optical modulators as an integral component of an electromagnetic beam detector (in this case, a stochastic cooling pickup) etched on a Teflon-based circuit board. The light shaded surface faces the beam and is a copper ground plane, while the pickup pads, traces, and modulators are on the back surface.

CONCLUSIONS

The present commercial status of optical technology is sufficiently advanced to already provide the means of substantially improving the accuracy, sensitivity, bandwidth, and signal-to-noise of accelerator instrumentation. The rate at which this technology is advancing makes optical fiber transmission and its associated hardware worth monitoring in the future.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the design and fabrication work of R. Pasquinelli and E. Buchanan. Their experience, engineering skills, and careful construction are responsible for the success of the optical fiber based microwave signal transmission and filter projects at Fermilab.

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