Fiber Fabry-Perot tunable filter for high-speed optical packet switching

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ABSTRACT

Tunable optical filters are important building blocks for All-Optical systems and networks. Fast optical tuning in several microseconds is necessary to perform high-speed optical packet switching. Multi-Gigabit/sec packet-switching will provide flexibility and higher network throughput when large numbers of users communicate simultaneously. One approach to achieve fast wavelength tuning is to use high-speed piezoelectrically-driven Fiber Fabry-Perot tunable filters (FFP-TFs). The requirement for tuning in microseconds raises a whole new set of challenges, such as ringing, thermostability and mechanical inertia control. It was shown that correlation between the mechanical resonance and optical response of the filter is important for the filter's speed and for mounting hardware and control circuitry optimization. These features together with the FFP-TF's high capacitance (~ 0.25 - 0.5 microfarad) are being folded into building a special controller to substantially improve the shape of the driving signal and the response of the filter. The resultant controller enables tuning the high-speed FFP-TF three-orders-of-magnitude faster than that possible with standard commercial FFP-TFs. The fastest switching time achieved is 2.5 microseconds. As the result, a new packet-switched media access control protocol is being designed to minimize the searching time. The filter scans only once through the entire optical region and then tunes to all the required channels one after another in a few microseconds. It can help update Rainbow-2 Broadcast-and-Select High-Speed Wavelength Division Multiplexing All-Optical network that currently has a circuit-switched protocol using standard FFP-TFs.

Keywords: Fiber Fabry-Perot tunable filters, optical switching, WDM, All-optical networks

1. INTRODUCTION

Digital networks are evolving toward distributed multimedia with a wide variety of applications with bit rates ranging from kb/sec (e.g., file transfer, telephony) to tens and hundreds of Mb/sec (e.g., HDTV, full motion uncompressed video), and in some cases approaching Gb/sec (e.g., campus backbones, supercomputer interconnections, and in interconnections of high-speed LAN's). Increasing rates and the burstiness of traffic sources lead naturally to systems based on the *fast packet switching* idea¹. The requirements of data buffering and processing of packet headers have resulted in *electronic solutions* for most of the existing fast packet switching nodes. However, optical fibers have changed the previous relationship between fast computers and slow wires. Fiber optics running at the speed of light can support data transfers significantly higher than Gb/sec. A few years ago Los Alamos National Laboratory (LANL) developed a network technology called the High Performance Parallel Interface (HIPPI) which runs at 0.8 and 1.6 Gb/sec. Optical-fiber transmission systems can easily achieve HIPPI rates and, in fact, are used today to transmit HIPPI over 10 km. In addition, these transmission systems have incredibly low bit error rates compared to copper-wire links, typically 10^{-9} , compared to 10^{-5} . Current Laboratory programs are requiring higher network performance capabilities, especially when using clusters of symmetric multiprocessor (SMP) computing systems. Such requirements are pushing

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the link speeds into the gigabyte/s range. Because of the fiber capabilities, it is obvious why the technology in broadband communications is moving towards *optics*.

Growing communications provide a strong impetus for developing high-speed networks capable of delivering increasing amount of payload under strict delay constraints. Single channel networks may not be able to provide the necessary level of service. Multiple concurrent channels over a single fiber using wavelengths as a channel discriminator offer a technique for building very fast networks. This approach takes advantage of the vast bandwidth of optical fiber via *wave-length division multiplexing (WDM)*^{2,3}. With WDM, it becomes feasible to provide many optical channels in a single medium. The fiber is not used simply as a replacement for copper wires but to carry multiple channels of various data types with each channel assigned unique wavelength.

At the same time, *fast switching* is one of the important requirements for high-speed packet-switched optical networks. It needs a discriminating component that can detect the destination of incoming traffic and route that traffic to a proper end node. For high bandwidth networks, this component is usually an electronic switch in the center of the network. Not only must this route the incoming message to the proper destination, but with gigabit and higher bandwidths, it must do this in a few microseconds in order not to impact the overall performance of the network. In addition, an electrical to optical conversion of the data-stream is incorporated at the electronic switch in such a network that affects performance and reliability. To better utilize fiber optic networks that support gigabit and higher transmission speeds, electronic switches should be replaced by optical switches in the transmission path. At this point, the network becomes an *all optical network*. From the first conversion of the signal from at the computer to the final re-conversion to data at the destination, it propagates through glass and does not need to go through any electro-optical conversion in between. Due to this, significant effort is focused on *fast optical switching*.

Support of *packet switching* is also critical for multi-gigabit/s all-optical networks to provide flexibility and higher throughput. Rather than a dedicated circuit-switched connection between two parties, like telephones, computer networks send data in packets, a few million times a second, and each of the packets needs to be switched to its proper destination. Optical tuning in *several microseconds* is necessary to perform *high-speed optical packet switching*. However, neither the current lasers nor filters can tune from one wavelength to another faster than a few thousand times a second. This limitation is a serious drawback for links to high-end computers and the network interconnecting them. Efforts to build a faster laser with broader bandwidth, a filter with faster tuning, or new ways to use bandwidth to simulate packet switching are taking place at large number of laboratories. Today, lasers and receivers switch fast enough but they still lack the ability to cover the entire bandwidth needed. Some optical tunable filters have larger bandwidth than tunable lasers but the slowness of current filters (*millisecond tuning speeds*) restricts optical networks to circuit-switched applications. In this paper we report about an ongoing experimental effort aimed at the development of very important building blocks for high-speed optical packet-switched networks -- *optical high-speed tunable filter (TF)* and *special high-speed TF's driver*.

2. IMPACT OF TF's SPEED ON RAINBOW-2

An existing truly all-optical gigabit network is the IBM Rainbow-2 network. It was developed under a CRADA established in 1991 to couple LANL's Gigabit networking expertise with IBM's Rainbow Network development⁴. The prototype Rainbow-2 network was installed in the Advanced Computing Laboratory (ACL) at Los Alamos where LANL made performance measurements. The network offers the potential for building large networks supporting hundreds of nodes and offering each node capacity of up to 1 Gbit/s using WDM⁵. The current Rainbow-2 has a passive star-coupler that can interconnect up to 32 nodes in the 1.5 micron window. It was upgraded from 300 Mb/s to Gb/s as part of the collaboration with LANL. Each node has a fixed optical transmitter and tunable receiver (see Fig. 1). At each receiver, a piezoelectric FFP tunable filter is used as a Demultiplexer to select a desired wavelength⁶. The Rainbow-2 technology uses the SHIP (Simple Host Intersocket Protocol)^{4,5} protocol

developed by LANL that accelerates the processing speeds of the connected computers and supercomputers by offloading normal transport and network protocol work from a Host processor to a dedicated Protocol Processor. It takes advantage of large packet sizes (up to one Gbyte), fixed length, easily parsed headers, simple flow control, and an elimination of checksum error control.

Figure 1. Rainbow-2 network

Because of filter's tuning speed limitations, only *circuit-switching* can be supported efficiently by Rainbow-2. A triangular scanning waveform (sawtooth) was found to be best because of the filter's slow response due to its mechanical inertia. The application tolerates *milliseconds* switching time. In this particular implementation of Rainbow-2, the entire interval it scanned 25 ms. Each node is assigned one of 32 wavelengths and an address-identification code for transmitting data. In this circuit switched protocol, filters at inactive receivers search continuously through all network frequencies for broadcast messages. When, during the downward scan, an appropriate connection request is detected, the scan is ended, and a connection is established with the requesting node upon detecting an identification code.

A circuit-switched network is especially suitable for high-speed continuous streams of data, especially if the duration of the connection is relatively long. Examples of "connection oriented" services are video-conferencing and large file transfers. The Rainbow-2 optical circuit-switched network showed the potential efficiency of all-optical systems. Even in their initial forms they are more cost effective in bandwidth per dollar than any other network technology. Circuit switched networks are suitable now for many applications, however, in the near future when large number of supercomputers will need to communicate simultaneously, broadband multi-Gigabit/s *packet-switching* is necessary to provide flexibility and higher network throughput.

Part of LANL's collaboration with IBM called for placing the WDM high-speed optical network Rainbow-2 at Los Alamos to determine its feasibility in a "real world" environment with super computers and other high performance systems interconnected with this network. This evaluation of the performance of Rainbow-2 in the ACL has shown the necessity for deploying packet-switched rather than a circuit-switched network⁵. In contrast with circuit-switched protocols, the packet-switched *Media Access Protocol* needs much less time for tuning. In this case the filter scans only once through entire optical region. Then it tunes to all required channels one after another without additional scanning through all wavelengths (see Fig. 2). In our particular implementation the overhead of the tuning time has to be around 20-25 *microseconds* in order to keep it less than 20% (receiving time of the HIPPI burst is about 125 microseconds). As one can see, the current tunable optical filters are the major bottlenecks for

doing the fast packet switching optically. For this reason, a next important step in the development of all-optical networks is targeting the components required to achieve high-speed optical packet switching. That means improving the driving characteristics of the current filters by *three orders of magnitude*.

Transmitters (TXs) use fixed frequencies to transmit

Receivers (RXs) tune across frequencies to receive data from TXs

Scan:	look at all frequencies to determine TX
Tune:	move filter to specified frequency
Receive:	receive packet from TX
Arbitration:	Determine which packets are to be received during which receive period

Figure 2. Media Access Control Protocol (MAC)

3. PIEZOELECTRIC FIBER FABRY-PEROT TF

Microsecond tuning raises a whole new set of challenges, such as ringing, thermostability and mechanical inertia control. One of the approaches to achieve fast wavelength tuning as well as polarization insensitivity and low loss that are necessary to perform high-speed optical packet switching is to use *high-speed piezoelectrically-driven Fiber Fabry-Perot tunable filters (FFP-TFs)*. Piezoelectric Fabry-Perot filters are typically reported to have millisecond tuning speeds. In this paper we report tuning for FFP-TFs by Micron Optics Inc. (MOI) approaching one free spectral range (FSR) per several microseconds. To achieve those results we used special high-speed MOI FFP-TFs and a novel LANL stabilizing driver.

3.1. Structure of FFP-TF

The FSR of an ideal FFP-TF is related to cavity length (or distance between mirrors), l_c , by

$$\text{FSR} = c/2nl_c ,$$

where c is the speed of the light in vacuum, and n is the index of refraction of the cavity material. The finesse, F , of an ideal, lossless FFP-TF is related to mirror reflectivity, R , by:

$$F = \pi R^{1/2} / (1-R).$$

The bandwidth, BW, or wavelength resolution of the FFP-TF is simply

$$BW = FSR/F.$$

A sketch of the inner optical configuration of FFP piezo-tunable filter is shown in Fig.3(c). Low voltage piezoelectric (PZT) actuators are used to position two highly reflective mirrors. The air gap between the mirrors is only about 1-3 micrometers. The cavity is aligned in piezoelectric fixture, and tuning is achieved with PZT actuators that are capable of positioning accuracy of atomic dimensions. The construction of the FFP tunable filter with the single-mode optical fibers inside the cavity allows to avoid the need for lenses, collimated beams, eliminates the "walk-off" tendency, provides single-mode guidance and low-loss coupling⁷.

Figure 3. (a) Overall FFP-TF structure consisting of PZT, mounting hardware, and optical-fiber components; (b) improved high-speed FFP-TF; (c) inner optical configuration

Fig. 3(a)-(b) show sketches of two FFP-TF mechanical fixtures. Such a structure is inherently small and low mass, thus lending itself to the possibility of high-speed tuning. The steps taken to obtain high-speed performance specifically focused on reducing the mass of the PZT and its load that consists of the alignment hardware and optics. Initially, the alignment technology was designed into the mounting hardware much like the standard FFP fixture, except the length and outer diameter were reduced to reduce mass as illustrated in Fig. 3(a). Later in an alternative approach, the cavity alignment was carried out using external transition stages. This, in turn, allowed significant reduction in hardware mass as illustrated in Fig. 3(b), in addition the mass of the optical components was also reduced by reducing their physical size.

3.2. Characterization of high-speed FFP-TF

The five critical performance parameters of high-speed FFP-TF include tuning time per FSR, mechanical resonance, response linearity, and overall switching and settling time. Correlation between the mechanical resonance and optical response of the filter is important for the optimal high-speed tuning designs and for mounting hardware and control circuitry optimization. That is why one of our major efforts was focused on raising the mechanical resonance to beyond 100 kHz. FFP-TF mechanical fixtures were characterized, differing in PZT, mounting-hardware, optics, load mass, and PZT length, as listed in Table 1.

Table1. High-speed FFP-TF test result

	PZT length (mm)	PZT type (V/mm)	PZT Mass (g)	Hard- ware mass (g)	Optics Mass (g)	Load Mass (g)	First Res. (kHz)	TF0 (μ sec)	TF (μ sec)
TF1	16	12	4.4	5.2	0.5	5.7	40	7.00	1.76
TF2	10	18	3.0	5.2	0.5	5.7	52	9.40	1.76
TF3	10	18	3.0	3.0	0.5	3.5	59	5.90	1.66
TF4	16	12	4.4	3.0	0.5	3.5	34	7.00	1.36
TF5	10	18	3.0	1.2	0.5	1.7	68	3.90	1.10
TF6	10	18	3.0	0.1	0.3	0.4	75	2.68	0.94
TF7	10	18	1.8	0.1	0.1	0.2	113	2.44	0.84

A network analyser revealed a series of resonant frequencies in the fixtures' impedance transfer functions. The table shows the improvement gained by reducing of FFP-TF's structural mass. For example, TF3 exhibits resonances at 59, 123, 172, 400, and 980 kHz, though the last two resonances are very weak. By reducing the load mass from 3.5 g in TF3 to 0.4 g in TF6, these set of resonances moved out to 75 and 152 kHz, respectively (see Fig.4a). Furthermore, the magnitude of the first resonance decreased significantly. PZTs in TF1-TF6 have intrinsic resonances above 100 kHz; however, mechanical loading produces a first resonance below 100 kHz as shown in Table 1.

Next by reducing the load mass to 0.2 g in TF7, a dramatic improvement is obtained where the first resonance moved beyond 100 kHz, reaching 113 kHz (see Fig.4b). With regard to the PZTs, a smaller size PZT was specially fabricated for TF7. This small PZT has a mass of 1.8 g and a capacitance of 0.25 μ F. The previous standard PZT has a mass of 3.0 g, and a capacitance of 0.5 μ F. The PZT length dictates its intrinsic resonance, while the overall size and mass dictate its capacitance. The 10 mm PZT length has the first intrinsic resonance at $\sim$ 150 kHz, and a comparison among TF2, TF3, TF5, TF6, and TF7 demonstrated that the lower load mass indeed contributed significantly to the increase in the mechanical resonance frequency and reduction in magnitude. On the other hand, the lower capacitance is very desirable for easing driving and control requirements.

Fig.4 Impedance transfer characteristics for a) TF6 and b) TF7

3.3. FFP-TF's high-speed driver.

The switching speed of the FFP-TFs used in the fast mode is limited by acceleration of the mechanical motion and electrical loading of the drive voltage. An increase in the driving slew rates induces extensive optical ringing. There are also oscillations on the top of the square waveform that increases with the driving slew rate. The optical ringing is a combination of the driving waveform ringing and internal effects. It was suggested that it may be possible to improve the shape of the driving pulse and the response of the filter by proper design of the stabilizing electrical driver, but the resonance of the piezo element must be taken into account.

All of the FFP-TF's features together with its high capacitance (~ 0.25 - 0.5 microfarads) were folded into building a special high-speed stabilization controller to get a 'clean' square waveform of the driving electrical signal and decrease the PZT's resonance. The driver is designed to drive a single large capacitance piezo element, though maximum values of capacitance should not exceed 0.5 microfarads. Depending on the FSR of the filter under test, up to three drive levels can be selected by digital control. Normally two levels are used for FFP-TF evaluation. These levels are manually adjusted between 1.5 volts and 5 volts, then applied to a gain of 5 driver to provide a 7.5 to 25 volt range to match the FSR of

the piezo element. Levels below 7.5 volts are obtainable by changing circuit constants. This DC level is then applied to a variable bandwidth 8-pole Bessel filter, adjustable from 1 Hz to 100 kHz with a user operated control/readout. To decrease the PZT's resonance the Bessel filter smooths the edge transitions of the DC voltages before applying them to the output stage final circuit. The control of the variable bandwidth filter is managed by digitizing a zero to 5 volt signal to provide an 8 bit digital control word to the filter. The control word invokes one of the 256 bandwidths the filter can provide. Ringing and overshoot are thus controlled at the output when the filter drives the final stage with the amplified DC voltage.

In order to successfully drive large capacitive loads, a special output stage is required. This driver uses an Apex PA-51 device. It can drive over the full temperature range of -55 to +125 degrees C. Current limiting resistors of 0.8 ohms were chosen to prevent damage to the device when subjected to very large capacitive loads. Additional current drive above the 1 amp level now set, is available. Typical slew rate is 1.5 V/ μ s. There is a feedback feature that was not enabled yet but can use a DC "carrier present" voltage provided by an optical receiver. This input would enable the filter driver to make minute changes needed to track temperature drift in the laser source, or aging effects, such that optical carrier strength is always optimized at the receiver. Such a circuit would be needed in any commercial telecommunications system.

The resultant controller substantially improves the shape of the driving signal and the response of the filter. It helps to enable tuning of the high-speed FFP-TF three-orders-of-magnitude faster than that possible with standard commercial FFP-TFs.

Figure 5. (a) Fastest response time for TF5 without excess optical ringing with $T_{F0} = 3.9 \mu$ s; (b) fastest response time for TF5 with $T_F = 1.1 \mu$ s (note the two sets of traces of different time scales); (c) dependence of tuning speed on driving slew rates for TF1, TF2, TF3, and TF5

3.4. FFP-TF's performance evaluation

In our experiments we evaluated the response time (T_F) of the filter over the FSR for different FFP-TF's constructions. The fast rising and falling edges of a low-frequency square-wave electrical signal were used to rapidly scan the filter for the speed response. Initially, the driving slew rates and amplitudes were carefully adjusted to minimize the optical resonance due to electrical waveform ringing and internal effects. The most fast response times (T_{F0}) thus achieved without optical ringing for one reference are generally $<10 \mu s$. As an example, the fastest response for TF5 is shown in Fig. 5a, where $T_{F0} = 3.9 \mu s$. Further increase in driving slew-rates induces strong parasitic signals. The "ringing" is due to excessive voltage level as well as to internal effects such as excitement of PZT mechanical resonance. When the driving electrical signal is almost a step function, then sharp stopping at a desired wavelength excites back and forth motion and it periodically changes the small air gap inside of the filter. It causes periodical opening and locking of the filter. The results of that are shown in Fig. 5b, where $T_F = 1.1 \mu s$.

Results in Table 1 show all response times reaching 1-2 μs and the clear advantage gained by using the low mass MO's FFP-TFs and LANL's driver. Tuning speed versus driving slew rate plotted in Fig. 5c reveals an ideal linear relationship for low-speed operations and a nonlinear, dramatic increase in tuning speed for high speed operations. It's important to mention that we experimented with other tunable PZT Fabry-Perot filters. All of them had either substantially heavier mass or couple times higher than MO FFP-TF capacity. These reasons did not allow to tuning faster than at 100-200 μs even with use of LANL's driver. Also we were able to compare the performance of LANL driver and an old FFP-TF controller. LANL's driver substantially reduced the electrical oscillations of the driving signal and optical ringing in the filter thereby improving the response of the MO's FFP-TFs by a factor of two to three compared to the response obtained with the old FFP-TF controller.

Another set of experiments was carried out to measure tuning time, T_t , versus wavelength separation ($\Delta\lambda$) for (1) constant bias (V_b) and varying slew rate (SR), (2) constant SR, varying V_b . Fig. 6a shows the results for three different SR's: 1.95, 3.60, and 5.17 V/ μs . The T_t decreases with a higher SR. The T_t also decreases with higher V_b as shown in Fig. 6b. In this filter the PZT has 15V/FSR tuning characteristics at 1550 nm wavelength. The tuning response at 1.5V bias reflects the nonlinear characteristics of the PZT at low voltage. On the other hand, at higher V_b , where PZT has more linear behavior, the tuning response becomes independent of the bias voltage. Over all, the tuning time over 23 nm is well below 10 μs .

Figure 6. T_t vs. $\Delta\lambda$ for (a) constant $V_b=12$ V, varying SR; (b) constant SR=2.95 V/ μs , varying V_b .

We have also measured the fastest response times achieved for an optical filter without optical ringing for two references at 1545 nm and 1680 nm using the scanning regime. In this case the fastest response time achieved without ringing (T_{F0}) was 11.48 μ s. It was possible to operate at approximately 1 μ s/1V tuning speed that would be adequate for initial packet-switched systems if adequate PZT start and stop characteristics can be demonstrated.

For this reason the last set of experiments was performed to characterize the settling behavior of the filter when tuned between two arbitrary wavelength channels. Two types of light sources were used: laser sources and a spectrum-sliced source. Laser sources include a fixed wavelength source emitting at $\lambda_0=1534.3$ nm, and a HP tunable laser. The spectrum-sliced source is an erbium-doped fiber amplified-spontaneous-emission source having a comb wavelength output defined by a FFP filter. Comb wavelength spacing of 4.8 nm and 1.0 nm was used. The purpose of using two different light sources here is to observe whether there is any evident difference in the filter response due to a source. One would expect little difference if the filter BW is relatively wide compared to the source linewidth. In such a case, it is very convenient to establish a wavelength-switching characterization and demonstration setup using a spectrum-sliced source. Two groups of wavelength switching experiments are reported below, each using a different combination of the above mentioned filters and sources.

Figure 7. Settling behavior of the filter tuned between two arbitrary wavelength channels.

(a), (c) $T_s=20$ μ s; (b), (d) $T_s=10$ μ s; and (a), (b) $\Delta\lambda=1.97$ nm, $V_d=1$ V; (c), (d) $\Delta\lambda=4.17$ nm, $V_d=2$ V

The first group of experiments characterize the laser wavelength switching response of TF5. The driving voltage step (V_d) is incrementally set to 1, 2, 3 and 4V, with the high level tuned to λ_0 , and the low level defining the resonance wavelength from HP laser. In Fig. 7(a) the Bessel filter in the high-speed FFP-TF driver is tuned to give an approximate switching time (T_s) of 20 μ s. Note that T_s is defined here approximately from the previous peak prior to turn-off to the first oscillation peak of the turn-on. T_s is approximately 20 μ s over a wavelength tuning range $\Delta\lambda=1.97$ nm was obtained from a lower $\lambda_1=1532.33$ nm to λ_0 with $V_d=1$ V. The optical ringing is very slight, though the resonance condition quickly decays due to PZT drift. As a comparison, Fig. 7(b) reveals a stronger optical ringing from a faster switching time of $T_s=10$ μ s. Fig. 7(c) and (d) shows switching from $\lambda_2=1530.13$ nm to λ_0 ($\Delta\lambda=4.17$ nm) with $V_d=2$ V respectively over $T_s=20$ μ s and 10 μ s, clearly indicating a stronger ringing for a higher V_d and higher slew rate.

Figure 7. Settling behavior of the filter tuned between two arbitrary channels, $\Delta\lambda=4.8$ nm, $V_d=2.4$ V:

(a) $T_s=32.7$ μ s; (b),(c),(d) $T_s=20$ μ s; (a),(b) $f_d=69$ Hz; (c) $f_d=5$ Hz; and (d) $f_d=10$ Hz

The second group of this set of experiments characterize switching time T_s of TF5 using a spectrum-sliced source of a wavelength spacing ($\Delta\lambda$) = 4.8 nm. Fig. 8(a) shows switching over 4.8 nm in 37.2 μ s with V_d =2.4 V. There is little ringing in the fast time scale, while the slow time scale shows quick resonance decay. Fig. 8(b) shows a switching in 20 μ s with the same V_d =2.4 V over 4.8 nm. A slight ringing is observed followed by a quick resonance decay. The above two experiments were performed at a low drive frequency f_d =69 Hz. Using the same general driving condition as the above, Fig. 8(c) and (d) show switching with f_d =5 kHz and 10 kHz, respectively. Note that T_s stays fairly constant around 20 μ s, while the switching optical patterns follow the driving waveform very well despite optical ringing.

4. SUMMARY

We propose the use of a high-speed PZT FFP-TF together with the high-speed driver for gigabit optical WDM broadcast-and-select networks to perform fast packet-switching. This effort could be used to upgrade the IBM Rainbow-2 Broadcast-and-Select High-Speed WDM All-Optical network from a circuit-switched to a packet-switched environment.

Through the experiments described, fast switching operation has been confirmed. The fastest switching time achieved without ringing T_{F0} is 2.44 μ s and with ringing 0.84 μ s that is three-orders-of-magnitude faster than that possible with standard commercial FFP-TFs. Also the experiments on characterizing the settling behavior of the filter when tuned between two arbitrary wavelength channels have shown that T_s stays fairly constant around 20 μ s, while the switching optical patterns follow the driving waveform very well despite optical ringing.

The results imply that it is possible to implement a proposed MAC protocol with the tuning time around 20 μ s in order to keep overhead less than 20% in supercomputer interconnecting networks. Also, a switching response as fast as 20 μ s will satisfy the recommendations of Society of Motion Picture and Television Engineers (SMPTE) for video switching applications.

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