I. Introduction

We proposed to develop the key enabling technologies for a 100Tb/s aggregate capacity router with an optical switching core and to integrate them in a scaled-down, proof-of-concept router architecture. The two main problems for 100Tb/s routers are the switching core and the scheduler. An attractive solution for the scheduler has been proposed based on a two-stage switch, which simplifies considerably the scheduler at the expense of the switch hardware complexity (see Section III and references [9,10]). An optical switching core is proposed that would complement the two-stage switch scheduler and permit scaling to 100Tb/s.

The focus of this work is on the optical switching core that can scale to an aggregate capacity of 100Tb/s. We proposed to use WDM technologies to construct optical switching cores that will be lower in cost, size and power dissipation than their electronic counterparts. WDM technologies are very mature at this point because they have been developed for optical transmission systems. It would be advantageous to be exploiting the same platform to make optical switching fabrics. The switching fabric is based on using a broadcast and select switch with tunable filters. The switching fabric is a star coupler, and the tunable filters are based on tunable, thin-film structures.

Key enabling technologies required for the broadcast and select switching core are developed in this program. The key components and sub-systems are: (i) fast tunable filters; (ii) surface-normal modulator arrays; (iii) supercontinuum light source; and (iv) broadband amplifiers. At the University of Michigan laboratories, the supercontinuum light source and broadband amplifiers have already been studied and developed. Therefore, the thrusts early on in this program are to develop the fast tunable filters and surface-normal modulators. Then, the four sub-systems are to be integrated to demonstrate a scaled-down version of the optical switching core.

Internet protocol (IP) is already or will soon be the dominant form of traffic on the transmission systems. Therefore, the switching fabric required will be in the form of routers. In addition, the dominant cost in most optical networks is the optical-to-electrical (O/E) or electrical-to-optical (E/O) conversion. If optical routers can be made that reduce or minimize the number of O/E/O conversions, then there can be a potential simplification and cost reduction in the network. For example, cost savings and network simplification can be achieved if a switch can be developed that combines the routing functionality with the optical cross-connect (OXC) functionality. Since about 80% of the traffic to any node is by-pass traffic, the OXC/router combination can lead to significant reduction in the number of O/E/O conversions. Such an OXC/router combination can be implemented by using the same WDM on the inside of a router switching core as is used in the transmission system surrounding the router.

One relevant question is whether a 100 Tb/s aggregate capacity switching core can be implemented with DWDM technology. By the time such a project is implemented, it would be reasonable to assume that 40 Gb/s line rates are standard. Also, in a few years we expect that the telecommunications window of 1400 to 1650 nm (250 nm wide) should be available due to advances in metropolitan area networks. Moreover, a spectral efficiency as high as 4 bit/sec/Hz should be feasible using sophisticated coding, super forward-error-correction and good filtering technology. With this high spectral efficiency, it would be possible to put 40 Gb/s channels on 12.5GHz (0.1 nm) channel spacing, meaning that the telecommunications window could hold 2500 channels. Therefore, a 100 Tb/s aggregate capacity should be possible for 40 Gb/s channels and 2500 channel count, but it will be definitely challenging.

![Figure I.1 Relative performance increase of various technologies [1].](image)

With advances in fiber-optic transmission, the bottleneck for backbone IP networks is shifting to the router [1]. As an illustration, consider Figure I.1, which compares the relative performance increase of various technologies and bandwidth drivers over the past few years. DRAM access rates increase 1.1 fold every 18 months, while Moore’s
Law leads to processors that double in capacity every 18 months. The router capacity, which takes advantage of the Moore’s Law advances as well as router architecture advances, has steadily increased at roughly 2.2 times every 18 months. In comparison, dense wavelength-division multiplexed (DWDM) link capacities have doubled roughly every 8 months. On the other hand, the bandwidth driver, the Internet, is estimated to be doubling roughly every year. Therefore, while transmission capacity grows faster than the Internet growth, the router capacity has not been able to keep pace with the Internet. Hence, the key problem that will be faced by networks in the near future will be the need for high-capacity routers in the backbone that can interface to the DWDM links.

**What is Routing?**

To define the problem faced by the network, the first step is to define what is routing. In general, an IP network will consist of a set of core routers that are interconnected by fiber-optic links. The user sends data packets, which have embedded in them a destination address within the header. The router examines the header, does a look-up in a routing or address table to find the next hop, updates the header, and then sends the packet toward its destination. The packet will generally pass through several routers before reaching its destination.

A generic router architecture is illustrated in Figure I.2 [2]. On the most left side are the entering packets, and on the most right side are the exiting packets. The ingress line cards perform header processing, where a look-up in a routing or address table occurs along with the update of the header. The packets are then switched through a backplane or switched backplane. Finally, the output line cards have output buffers to avoid collision for multiple packets seeking the same output fiber.

![Figure I.2 Generic router architecture [2].](image)

**II. Evolution of IP Routers**

The first routers were very simple, using a shared backplane with a number of line interfaces that plug into that backplane (Figure II.1). This generation of router typically has an aggregate capacity less than 0.5 Gb/s. Each of the line interfaces can be connected off to a different type of network, and a per line specific function is performed on each of the line interfaces. The CPU processes each of the packets to make a forwarding decision. As in all packet switches, there is also buffer memory, since there can be oversubscription to a particular output link. For the maximum performance of this type of system, there are several limitations. First, the amount of storage in the buffer memory as well as the speed of the memory is a limitation. Second, the CPU capacity is a limitation, since
it needs to process every packet to determine their destination. Third, the capacity of the backplane is a limitation, since every packet needs to traverse the link at least twice.

The second generation packet switches are often called caching routers, and the idea is to off-load the CPU and memory from having to process every packet. This generation of IP routers typically has an aggregate capacity less than 5 Gb/s. A routing decision is attempted by using the small part of the total look-up table that is stored on each of the line interfaces, and the local buffer memory for the packets coming in on that interface (Figure II.2). Therefore, when there is a hit on the cache – i.e., a destination that the packets have recently been routed to – the packet can be sent on the bus to the egress line card without having to pass through the central CPU and buffer memory. Thus, the CPU and buffer memory are less of a limitation, and some of the packets need only to traverse the backplane once. This technique is also often called fast-path/slow-path routing, where the fast path corresponds to when there is a hit on the cache and the slow-path is when the packet enters the CPU and buffer memory. The performance of this type of system is determined by the size of the cache and the difference in speed between the slow and the fast paths.

Over the past few years it was found that the caching technique became less effective, because the locality that makes the cache work began to erode. Caching works well when packets are generally from the same sources and heading to basically the same destinations. That was true early on because the network was faster at the edge than it was in the core. However, as core router performance improved and the core was no longer the bottleneck, the situation changed. With high performance core routers, there is a lot of multiplexing of edge data onto core data, so it is much more likely that adjacent packets will be from completely different flows of data. Thus, the locality is removed, and caching is much less effective.

![Switched Backplane](image1)

![Optical Link](image2)

*Figure II.3 Third generation routers [3]. Figure II.4 Fourth generation of routers [3].*

The third generation packet switches try to remove the bottleneck associated with the shared backplane. This is accomplished by replacing the backplane with a switch, which allows multiple transactions simultaneously (Figure II.3). This generation of routers has an aggregate capacity typically less than 160 Gb/s. The third generation of routers used a switched backplane, where a switch such as a crossbar replaces the linear backplane. As an example, two packets can be simultaneously switched on the switched backplane as long as they are coming from different sources and are going to distinct destinations (right side of Figure II.3). Because of the parallel structure, the design is architecturally faster as well as electrically faster. Most of the core internet routers and ATM switches in use today are built in this manner.

The next problem that is faced with the router is that only a certain number of line cards can fit into a standard rack. For example, telecommunications racks are limited to a width of 19 inches and a height of 7 feet. Typically, about 14 to 16 line cards can be fit into one rack, and after that the third generation router design runs into trouble. Therefore, the general progression for further capacity routers is toward multiple-rack systems (Figure II.4). Partitions are made in the system, and there is a separation between the switch and the line cards to permit distribution over multiple racks. This architecture defines the fourth generation packet switches. This is also the first point at which optics enters the router, since short-range optics is used to connect the switch with the numerous racks of line cards. This generation of routers, which is currently under development, is expected to have an aggregate capacity between 0.3 Tb/s and 10 Tb/s.

**III. 5th Generation Router: Optical Switching Core**

A router can be broken down into a number of parts including line cards, route processor, interconnect for multi-rack system (i.e., a system with more than 16 line cards), switching fabric and scheduler. All of these parts must be simplified and scaled to build a multi-terabit router. The line cards might be simplified using a reduced format, such as MPLS/GMPLS, where label swapping replaces a more complicated header table look-up for global addresses in
IP. The scheduler can be simplified by using a multi-stage switching fabric, so long as the switching fabric is relatively inexpensive.

Optics offers the solution for the interconnect and switching fabric. For multi-rack systems, short range optics is already employed between racks. In switching fabrics the fundamental problem for electronics is that it takes roughly an entire rack to construct a 2 Tb/s switch. Hence, optics can be beneficial if it can reduce the size, cost and power dissipation compared to electronics. Moreover, the number of O/E/O conversions can be reduced if optics for the switching fabric is combined with the interconnect — i.e. use a fiber-based switching fabric. Our aim is to design and implement an optical switching core that also serves as the interconnect.

![Figure III.1 “Fifth generation” router architecture.](image1)

![Figure III.2 A star coupler based switching fabric architecture.](image2)

The architecture of our “fifth generation” router for up to 100 Tb/s aggregate capacity is illustrated in Figure III.1. Here, the racks of line cards remain as in the fourth generation routers described earlier. However, the switching fabric and fiber interconnection are combined, leading to the removal of the O/E/O conversion around the electronic switching fabric. Whereas the fourth generation router uses short-range optics (i.e., typically 1.3 [μm or 850 nm light) between the line cards and the switching fabric, in the proposed design the optics is the same DWDM wavelengths and technology as used in the fiber-optic links.

Based on the above discussion, the goals of the design of the optical switching core include the following:

- Low cost, small size and low power dissipation;
- Interconnect and switching fabric combined;
- Functionality of router and optical cross-connect;
- Minimal impact on line cards;
- Switching time of devices hidden.

### Broadcast & Select Switching Fabric

We propose a switching fabric based on using a broadcast and select switching fabric and tunable filters. The fabric could be a star coupler with fiber leads (Figure III.2). The tunable filters can be made in arrays and placed adjacent to the star, and multimode fibers can be used between the tunable filters and the receiving line cards. Compared with other proposed approaches, such as tunable lasers [4], diffractive MEMS devices [5], electro-holographic elements [6] or beam steering devices [7], the tunable filter approach is a simpler device with much simplified packaging requirements. Since the tunable filters are capacitive devices, the continuous power dissipation is also minimized. Also, since the tunable filters can be made in arrays, the switching fabric can be made compact.

Other benefits of the broadcast and select approach include:

- Passive, scalable, transparent switching fabric;
- Line cards minimally impacted because tunable filter and circuits in common bay equipment racks;
- Multicast and broadcast traffic without copies;
- OXC/Router functionality combined;
- Switching fabric and interconnect combined without intervening O/E/O;
- Hitless reconfiguration and hiding switching time possible.

Moreover, this design can be among the lowest cost approach. For example, the power splitters and taps are generally cheaper than wavelength-dependent multiplexers and demultiplexers. Also, since the distance involved is relatively short, the lasers and modulators do not have to meet the stringent requirements of long-haul networks. For instance, integrated electro-absorption modulated distributed feedback lasers can be used, which would be cheaper than laser diodes with external modulators. Also, as described below, for large channel count systems, broadband sources
such as supercontinuum (SC) sources can be employed. Finally, for the relatively simple architecture of Figure III.1, in principle all of the components can be off-the-shelf except for the fast tunable filters.

**Architectural Challenges and Mitigating Techniques**

There are a number of challenges in using a broadcast and select based switching fabric while trying to minimize the size, cost and power dissipation. The first difficulty relates to scalability issues. There is an inherent $1/N$ loss in a N-port star coupler [8]. For 2500 channels as an example, the in-principle loss is 34 dB. One way of dealing with this loss is to replace the star coupler with a WDM combiner followed by an optical amplifier and a power divider (c.f., Figure III.3). This approach has the advantage that near unity gain can be provided for by-pass traffic, hence enabling the OXC/router functionality to be combined.

**Figure III.3** Method to deal with losses in the broadcast and select switch.

A second challenge relates to emulating fast switching using low-cost components. The fact remains that 50-100 nsec optical devices still cost considerably less than sub-nanosecond optical switching devices. Three basic techniques can be used to accommodate slower components (Figure III.4): (a) speed-up of the switching fabric; (b) aggregation of a number of cells into super-frames; and (c) ping-ponging between different filters. In the latter case, one filter is used for channel selection while the other filters are reconfiguring. The speed is then set by the electrical switch behind the receivers, which can be in the sub-nanosecond range.

**Figure III.4** (a) Speed up; (b) Aggregation and super-frame; (c) Ping-pong between two filters.

A third challenge of very large routers is the scheduler for the switching fabric. The scheduler can be made trivial – i.e., a simple round robin scheduler – by using a two-stage switch (Figure III.5) [9,10]. For this solution to be attractive, however, the switching fabric must be relatively compact and low-cost. The broadcast and select with tunable filter approach is probably best suited to the multi-stage switching technique, but issued remain including:

- How to avoid mis-sequencing of packets in a stream?
- Does the switching fabric need to reconfigure every cell cycle?
- Are line cards needed in all three locations, or can only two sets of line cards be used?

For example, Figure III.6 illustrates two architectures that combine the two-stage switch with the broadcast and select design. In the first at the top of Figure III.6, two switches are simply cascaded, leading to three sets of line cards and two star coupler switches. On the other hand, if the function of the first set of line cards can be combined into the second set of line cards, then a simpler configuration at the bottom of Figure III.6 can be employed. Since
for a large system the line cards are the most expensive and the largest volume of equipment, the second configuration can lead to a considerable simplification over the first.

Figure III.7 Supercontinuum source to be used for large channel count in common-bay equipment.

A fourth challenge of large number of line cards and a WDM approach is the cost of the many wavelength light sources. For more than 100 channels and 40 Gb/s or higher rates per channel, a very attractive approach is to use a supercontinuum (SC) light source, which we have developed at the University of Michigan (Section IV.2) [11-14]. The challenge of this approach is low-cost, high-speed, broadband modulators on each line card (c.f., Figure III.7). However, the benefits of the approach include:

- One modelocked source and a common SC set-up – this can be placed in common equipment bay with minimal impact on line cards;
- Channel spacing set by passive WDM demultiplexer that carves out channels from the SC;
- For 40Gb/s (or time-multiplexed to 160Gb/s), only one expensive modelocked source required. SC copies the pulses to many wavelengths;
- Each line card requires a modulator, but individual wavelength laser diodes are not required – if modulator is broadband, then there are only a few different types of parts required.

The construction and properties of the SC light source as well as a proposed method of making the surface normal modulators are discussed in the components and sub-systems section below.

IV. Key Enabling Technologies for Optical Switching Core

IV.1 Fast Tunable Filters

We propose a multilayer thin-film filter with electro-optic spacer layers (optical cavities) as the foundation for fast tunable filters. Fixed filters based on dielectric stacks or layers are a well known technology, and they have the benefit with low insertion loss (typically ~0.7 dB in commercial devices). Also, multiple cavities can be used to tailor the passband spectral shape as well as passband width. For example, Figure IV.1.1 shows the transmission for a Fabry-Perot filter, a three-stack cavity filter, and a 8-10 cavity wideband filter that can be used an optical add/drop multiplexer. Thus, the thin film filter serves as a platform for a number of optical devices. We propose to make these designs tunable by replacing the dielectric spacers with electro-optic materials. Then, by applying a voltage across the cavities, the refractive index changes, and the passband shifts. Of the various electro-optic materials
available, perhaps the most well-studied and with the most mature fabrication technology is lithium niobate. Therefore, we will start with lithium niobate spacers in our first generation, which has the additional benefit of very fast response (i.e., it is known to operate at 40 Gb/s and higher modulation rate).

As a starting point, we have designed a three-cavity filter using lithium niobate in the spacer layers and high-reflectivity mirrors based on alternating quarter-wave thick layers of SiO$_2$ and TiO$_2$ (Figure IV.1.2a). In addition, doped silicon quarter-wave layers are used as the electrodes deposited adjacent to the electro-optic layers. There are 86 layers altogether with a total thickness of 21.924 μm. The transmission characteristics are illustrated in Figure IV.1.2b. The design has a –1 dB bandwidth of 0.276 nm (34.5 GHz) and a -30 dB bandwidth of 1.3 nm (162.5 GHz). Thus, this design meets the typical criteria for filters using 10 Gb/s channels on 100 GHz channel spacing for which the -30 dB bandwidth should be less than 200 GHz and -1 dB bandwidth should be greater than 25 GHz.

Figure IV.1.3 shows the simulated tuning characteristics of the filter. The calculation assumes a value for lithium niobate of $r_{\text{el}}=8.6 \text{ pm/V}$, which is measured at high frequency modulation with light at 633 nm. For an applied field of 2 MV/cm, the refractive index of lithium niobate is changed by .0093, and the passband shifts by 4.4 nm. Therefore, if the electric field is varied between –2MV/cm and +2 MV/cm, the peak-to-peak tuning range will be 8.8 nm.
The polarization dependent loss is also studied for this longitudinal electric field configuration. At normal incidence there is no polarization dependence, but the polarization sensitivity increases as the incident angle increases. For example, the simulations show that at a 4 degree incident angle, a 0.1dB polarization dependent loss is observed within the -1dB pass band (Figure IV.1.4).

**Drive Electronics**

In the filter described, we need to apply an electric field to obtain the tuning function. This is achieved by growing electrode layers adjacent to the electro-optic layer. In a three-cavity filter, we thus have six electrodes. To obtain a good tuning range we need to apply a high drive voltage, but complications arise when fast tuning is required. The drive voltage required is about 215 V. Since we must also allow for a voltage drop inside the electrodes, 250 V is used as for the required voltage magnitude from our driver. These calculations assume that the thin film properties approach the bulk properties. Therefore, the voltage requirement is likely to be higher if the electro-optic coefficient of the thin film is lower than the bulk material.

The filters will be designed to switch channels in a time range of 50 – 100 ns. This requires the high voltage driver to have a bandwidth in the tens of MHz range and a slew rate on the order of 5000 V/μs. High-speed, high-voltage ICs are used in many applications such as transducer excitation and high-resolution CRT monitors. Such ICs can be used for cases where the drive voltage swing is achievable. For voltage swings far greater than those achievable with commercial ICs, a custom design is needed. A custom designed driver circuit will need to be capable of switching up to ± 250V in 100 ns and at a high repetition rate.

Another constraint to be considered when designing the circuit is the time constant of the filter itself. The load here is the capacitance exhibited by the thin film. The time constant of the drive circuit and filter will impose an upper limit on the repetition rate. For the lithium niobate filter, the capacitance is of the order of tens of picofarads.

**Fabrication**

Standard optical thin-film filter fabrication techniques can be used for deposition of all layers in the filter. Energetic deposition processes, such as ion-assisted electron beam deposition, are advantageous for producing high-density films. Film microstructure in conventional thermal evaporation is strongly columnar, density is low and deposited films are susceptible to index change with humidity. An energetic process such as ion-beam assisted deposition imparts energy to the condensing film, eliminating the columnar microstructure and thereby producing a bulk-like film. Such bulk-like characteristics are especially desirable in the electro-optic layers to maximize the electro-optic coefficient and reduce tuning voltages. In addition, optical monitoring of the films is needed to achieve DWDM-grade filter performance. For example, simulations suggest a thickness error standard deviation of 0.001% on individual layers to achieve an in-band ripple of 0.1 dB and a low spread in the pass band location. Such a low error tolerance is outside the capability of coating systems that monitor the optical thickness of each layer independently. However, turning point monitoring, where the reflectance or transmittance of the composite thin-film structure is monitored and deposition of individual layers is terminated at the extrema of the monitored signal, can achieve the accuracy needed when used in conjunction with thickness monitors.

Further steps in the deposition process comprise patterning of the deposited films and thermal processing of the lithium niobate layers. Patterning of the deposited films can be performed using lithography (10 μm) and the lift-off or shadow mask methods. In addition, thermal processing of the lithium niobate layers may be needed to improve optical and electro-optical properties.

**Challenges**

A number of challenges relating to fabrication and operation of the tunable filter remain. First, it is well known that physical vapor deposition of lithium niobate typically results in films deficient in lithium compared to the starting material. Since the electro-optic properties depend on composition of the deposited film, mitigation of lithium volatilization, for example, by increasing the lithium/niobium ratio in the starting materials, may be required. A second fabrication challenge is achieving properties of the lithium niobate films comparable to those of the bulk material. In this regard, energetic deposition processes that produce bulk-like films can be utilized. Furthermore, details of the thermal procedure for re-crystallizing the lithium niobate films need to be determined, and it may be necessary to pole the film to re-orient the c-axis normal to the substrate to achieve low polarization dependence in the longitudinal configuration.

Long-term stability of the filter characteristics is as yet unknown. Crack formation has been observed under high electric fields in bulk lithium niobate, and the possibility of such a failure mode in the tunable filter requires investigation. In addition, depolarization and photorefractive effects in lithium niobate layers may limit the useful
life of the filter. A further risk concerns the combination of high voltages and slew rates required to achieve the target tuning range. Present designs require +/- 250 V at a slew rate of 5000 V/us to tune over ~ 10 nm in 100 ns. Such high voltages at high slew rates not only represent a challenge in their own right that need to be addressed through special circuit design techniques, but also raise concerns about compact filter packages and cross-talk in multi-element arrays.

IV.2 Supercontinuum Light Source

SC generation in fibers is an attractive candidate for the common bay light source when the channel count exceeds 100, particularly with channel speeds of 40 Gb/s or higher. A broadband, coherent output from the continuum can be used to produce short pulses at multiple wavelengths simultaneously. The alternative for 40-100 Gb/s would be to use multiple modelocked lasers or pulses carved by electro-absorption modulators from a cw laser. However, the cost of such an approach is prohibitive since multiple lasers are required that themselves are expensive, the sources often require dispersion compensation to unchirp the pulses, and stabilization techniques are needed to set the wavelength and timing of the sources. In contrast, a continuum source uses one modelocked laser as the driver, and the nonlinear continuum generation in the fiber makes replicas of the pulses at a wide range of wavelengths. Only one laser needs to be synchronized, and the wavelength stability and spectral and temporal widths of the pulses is set by the passive filters used to carve the continuum. Thus, the short fiber continuum source has:

- multi-wavelengths that are generated coincident in time;
- well-understood and controllable mechanisms underlying the continuum generation;
- stability against mechanical and environmental fluctuations.

Our group at the University of Michigan has studied and developed the SC source [11-14]. We generate in 2 m of dispersion-shifted (DS) fiber more than 200nm of spectral continuum that is flat to less than +/- 0.5 dB over 60nm. The continuum exhibits excellent piecewise coherence as evidenced by obtaining <500 fs pulses that are pedestal-free to >28 dB, even when the spectrum is carved more than 70 nm from the pump wavelength. In addition, the timing jitter of the carved pulses indicates no degradation compared to the source laser. By generating the continuum in a length of fiber that is three orders of magnitude shorter than in similar experiments [15], we obtain a very stable source for the multi-channel applications.

We investigate the continuum generation using the experimental set-up in Fig. IV.2.1. A passively modelocked erbium-doped fiber laser generates a 15 MHz train of 470 fs, transform-limited, hyperbolic-secant pulses centered at 1560 nm. The pulses broaden dispersively to ~980 fs with propagation through 5.1 m of SMF-28 fiber pigtailed and a polarization controller. An erbium-doped fiber amplifier (EDFA) consisting of 1.5 m of 2000 ppm-doped Er gain fiber amplifies the signal to an average power of 5 mW. Following the EDFA, the pulse is compressed to ~120 fs through soliton compression effect in 2 m of standard fiber. The energy per pulse is approximately 200 pJ. The compressed pulse is launched into the 2 m DS fiber with D = 1.3 ps/nm-km and a dispersion slope of ~ 0.07 ps/nm²-km. A polarization controller sets the state of the signal polarization at the input to the EDFA, and a variable attenuator sets the signal power. Diagnostics consist of an optical spectrum analyzer, autocorrelator, fast photodiode and RF spectrum analyzer.

![Diagram of experimental setup]
A sample continuum generated by an average signal input power of 3.2 mW is indicated in Fig. IV.2.2. The continuum has a 20 dB bandwidth of 211 nm and a 61 nm wide spectral region between 1475 to 1535 nm that is flat to within +/- 0.5 dB (inset). The power spectral density across the flat region is approximately -18 dBm/nm. The peak in the vicinity of 1560 nm includes low intensity energy that was not compressed in the soliton, amplified spontaneous emission, and seed pulse energy that is polarized orthogonally to the continuum. The polarization controller setting is critical to optimizing pulse compression in the standard fiber by aligning the seed pulse polarization with a polarization eigenmode of the fiber. Polarization does not appear to play a role in the continuum generation process, however, since the SC spectrum changes negligibly when the DS fiber is manually manipulated.

To measure the coherence of the spectrum, a 25nm bandpass filter (flat passband, Gaussian roll-off) centered at 1490 nm is used to carve the continuum. Then, the filtered pulse propagates through 22 m of $\lambda_c = 1560$ nm fiber to compensate for residual second order dispersion accumulated in the filter pigtails. The autocorrelation and spectrum of the pulse carved from the continuum at $\lambda_c = 1490$ nm are shown in Fig. IV.2.3. The autocorrelation shows that the 400 fs pulse is pedestal free to >28 dB with an excellent Gaussian fit, indicating a high degree of coherence among the carved spectral components and negligible incoherent power. The time-bandwidth product of the compensated pulse is ~0.45, assuming Gaussian fit of the spectrum, indicating negligible chirp across the broadened spectrum in this region.

To measure the timing jitter of the pulse, a 25nm bandpass filter centered at 1490 nm is used. The autocorrelation and spectrum of the pulse carved from the continuum at $\lambda_c = 1490$ nm are shown in Fig. IV.2.3. The autocorrelation shows that the 400 fs pulse is pedestal free to >28 dB with an excellent Gaussian fit, indicating a high degree of coherence among the carved spectral components and negligible incoherent power. The time-bandwidth product of the compensated pulse is ~0.45, assuming Gaussian fit of the spectrum, indicating negligible chirp across the broadened spectrum in this region.
To measure the timing jitter of the continuum output, we use the set-up in Fig. IV.2.4. The filtered continuum pulse train is incident on a fast detector with a 25 ps rise time and the RF spectrum is displayed on a 6.5 GHz RF spectrum analyzer. The timing jitter is evaluated by integrating the sideband energy of the 430th harmonic of the fundamental repetition rate over a 5 kHz span with 30 Hz resolution. A high harmonic is used to negate any effects of amplitude jitter on the measurement. The inset indicates the integrated power spectral density of the sidebands at this harmonic, and corresponds to the standard deviation of the repetition rate over the measured time span. Figure IV.2.5 shows the timing jitter of the seed laser pulses and the pulses carved from the continuum. The carved pulses show no jitter increase, even over a 10 ms measurement time.

**IV.3 Surface-Normal Modulators**

If the SC source is to be used in the common bay equipment as the light source for all of the channels, the next required element is an array of modulators (c.f., Figure III.7). We propose to use the same tunable filters described in Section IV.1 as the array of surface normal modulators. The concept is illustrated in Figure IV.3.1. The output of the SC is split up into the various wavelength channels using a demultiplexer, such as an arrayed-waveguide grating. Then, for each of these wavelength signals, a tunable filter with a square-like transfer function can be used to modulate the data, assuming that the filter has an adequate contrast ratio. An array of the filters can be made in a single structure, and each filter is tuned to the particular wavelength channel directed to it. For a high output, the filter is centered on the channel, and for a low output the filter is tuned away from the wavelength of the channel. For a square-like filter function with high contrast between the peak and minimum transmission, the filter tuned in and out of the channel wavelength serves as a good modulator. In addition, the tuning of the filter in and out of the channel requires much less than a π-phase shift, since the π-phase shift actually corresponds to the free spectral range of the device. In other words, because of the resonant nature of the cavity filter, the phase shift is reduced by the numerous round-trips in the cavity. Finally, the filter should be able to modulate at the desired high speeds, since the electro-optic response is fast and since the device has low capacitance.

*Figure IV.3.1 Concept of surface Normal Modulator*

**IV.4 Broadband Amplifiers**

Raman amplifiers are among the most broad band optical amplifiers available, and our group at the U-M has done pioneering work on the wideband amplifiers that has actually already been commercialized. In the past few years Raman amplifiers have experienced wide deployment in long-haul and ultra-long-haul networks because of the significant performance enhancement over other types of amplifiers. For example, distributed Raman amplification improves the noise performance and decreases the nonlinear penalties in WDM networks, thereby alleviating the two main constraints in dispersion compensated, optically amplified systems. The improved noise performance can be used to travel longer distances between repeaters or to introduce lossy switching elements such as optical add/drop multiplexers or optical cross-connects. Discrete and distributed Raman amplifiers can be applied at any wavelength range, with the gain band being determined by the pump distribution. Also, discrete Raman amplification can efficiently be integrated with dispersion compensation. Hence, Raman amplification permits wide bandwidth and long reach simultaneously. For instance, commercial systems in 2002 provide 240 channels at 10 Gb/s over 100 nm bandwidth (capacity of 2.4 Tb/s) over 1500 km with static optical add/drop multiplexers at every in-line amplifier site (roughly every 80 km). Of course, if less bandwidth is required, then the unrepeated distance can be even longer.
Our group has implemented an amplifier structure combining both lumped Raman and distributed amplification, and we have demonstrated the feasibility of transmitting 240 OC-192 channels over 1565 km standard single mode fiber. In this all-Raman experiment, a wideband 100 nm Raman amplifier is used both for the booster amplifier and the in-line amplifier (ILA). The ILAs use a hybrid distributed/lumped Raman amplifier in a three-stage configuration (Fig. IV.4.1). Dispersion and dispersion slope compensation is provided by the dispersion compensation fiber used as gain medium in the lumped Raman amplifiers (LRAs), and a static gain-flattening filter is used to obtain a substantially flat gain spectrum over 100 nm. Each LRA is composed of two stages separated by isolators to reduce double Rayleigh scattering, so that the resulting amplifier has a low MPI level.

The ILAs’ performance were tested in a testbed consisting of standard single-mode fibers and ILA’s placed roughly every 80km. Figure IV.4.2 shows the output spectrum for 240 channels after eight spans (~650 km total length) for a substantially flat input spectrum. Each ILA now has an output power of +24 dBm, corresponding to 0 dBm per channel for the 240 channels. With the use of dynamic gain equalizers placed periodically in the span (i.e., one or two in the entire 19-span link), transmission of all 240 channels over a distance above 1500 km can be achieved.