A frequency-selective optical switch capable of switching separate optical signals in a physical input channel to a selected output channel. A diffraction grating (12) spatially divides the input channel (10) into its frequency components, which pass through different segments of a liquid-crystal modulator (24). The liquid-crystal modulator segments (20, 22) are separately controlled to rotate the polarization of the frequency channel passing therethrough or to leave it intact. The channels then pass through a polarization-dispersive element (28) which spatially separates the beams (14, 16) in the transverse direction according to their polarization. A second diffraction grating (40) recombines the frequency components of the same polarization into multiple output beams (42, 44).
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Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

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FREQUENCY-SELECTIVE OPTICAL SWITCH USING POLARIZATION ROTATION

Related Applications
This application is a continuation-in-part of Serial No. 08/070,591, filed June 1, 1993.

Field of the Invention
The invention relates generally to liquid-crystal devices. In particular, the invention relates to liquid-crystal and similar devices useful for switching in a multi-frequency communication system.

Background Art
Communication networks increasingly rely upon optical fiber for high-speed, low-cost transmission. Optical fibers were originally envisioned as an optical replacement for electronic transmission media, such as high-speed coaxial cable and lower-speed twisted-pair cable. However, even high-speed optical fibers are limited by the electronics at the transmitting and receiving ends, generally rated at a few gigabits per second, although 40 Gb/s systems have been prototyped. Such high-speed electronic systems are expensive and still do not fully exploit the inherent bandwidth of fiber-optic systems, measured in many terabits per second.

All-optical transmission systems offer many intrinsic advantages over systems that use electronics within any part of the principal transmission path. Wavelength-division multiplexing (WDM) electronically impresses different data signals upon different carrier frequencies, all of which are carried by a single optical fiber. The earliest WDM systems did not provide optical switching but only point-to-point WDM.

Recent research and development have suggested that an all-optical network can be constructed having switching nodes that can switch the separate WDM channels (carrier frequencies) in different directions without the necessity of converting the optical signals to electronic signals. If such optical switching can be accomplished with simple optical components, a sophisticated optical network can be constructed at relatively low cost with
the high-speed electronics being confined to end terminals that require speeds of only the
individual channels and not of the total throughput of the system.

However, such optical switching needs to effectively separate the switched
channels. A cross-talk requirement of $20 \, dB$ is a minimum, $35 \, dB$ would be a reasonable
design requirement, $40 \, dB$ would be better. Also, the switching bands should be
relatively wide to accommodate significant frequency fluctuations in the optical
transmitters, particularly due to frequency chirping in directly modulated laser sources.
That is, the switch must have its frequency bands registered with the transmitter even
when the transmitting frequency is varying somewhat. The combination of a wide
switching band and low cross talk requires a flat-top switch spectrum. Furthermore, a
somewhat minimal WDM switch has a size of $2^4 \times 2^4$, that is, two physical input fibers and
two output fibers, each bearing four WDM channels freely switched from either input to
either output.

Cheung et al. in U.S. Patent 5,002,349 have suggested that an acousto-optical
tunable filter (AOTF) be used in such a WDM network, either at the switching node or at
the terminal end. However, AOTFs have many intrinsic problems, such as cross-talk
between adjacent-frequency signal. To date, these problems have prevented ATOFs from
being adopted into communication networks. The physical mechanisms of AOTFs seem
to preclude a good flat-top response.

Patel, sometimes in conjunction with co-inventors, has suggested that liquid-crystal
filters be used in such WDM communication networks; see, for example, U.S. Patents
5,111,321 and 5,150,236. Indeed, Patel has suggested in U.S. Patent 5,111,321 that a
liquid-crystal system could be used as a drop-add circuit. However, such a system appears
difficult to implement.

Weiner and collaborators have disclosed how an optical signal can have its
frequency-divided components separately phase-modulated or amplitude-modulated by
using a diffraction grating to divide the input signal into spatially separated frequency
components which are separately operated upon by a segmented modulator. See, for
example, U.S. Patent 4,685,547 to Heritage et al. Patel et al. have applied this concept to
a system incorporating liquid-crystal modulators, as disclosed in U.S. Patent 5,132,824.

The use of diffraction gratings for multiplexing in a WDM system has been

Nonetheless, the prior art fails to disclose an effective, economical optical switch for a WDM telecommunication system.

**Summary of the Invention**

The invention may be summarized as an optical switch, preferably using a segmented liquid-crystal modulator. The switch divides an input signal into multiple outputs according to the frequency components of the input signal. In particular, the input signal is spatially divided into its frequency components, which pass through different segments of a liquid-crystal polarization modulator. The different frequency components, depending upon their polarization impressed by the polarization modulator, are separated by a polarization divider. The frequency-divided components are then separately recombined according to their polarization, thereby producing two or more output signals that have been selectively separated according to optical frequency.

**Brief Description of the Drawings**

FIGS. 1, 2, and 3 illustrate respective horizontal, vertical, and isometric views of a polarization-sensitive 1×2 switch of the invention.

FIGS. 4, 5, and 6 illustrate respective horizontal, vertical, and isometric views of a polarization-sensitive 2×2 switch of the invention.

FIGS. 7, 8, 9, and 10 are graphs of experimental data of an embodiment of the invention.

FIG. 11 is a vertical view of a polarization-insensitive embodiment of the invention.

FIG. 12 is a vertical view of an alternative polarization-sensitive embodiment of the invention using Wollaston prisms.

FIG. 13 is a vertical view of an extension of the embodiment of FIG. 11 that has been made polarization insensitive.
FIG. 14 is a vertical view of a reflective embodiment of the switch of the invention.

**Detailed Description of the Preferred Embodiments**

The invention achieves all-optical switching of the frequency-multiplexed multi-channel optical signals by frequency-dividing an optical input signal into spatially separated channels, selectively changing the polarization characteristics of the frequency-separated channels, further spatially dividing the channels according to polarization characteristics, and the recombining the channels of similar polarization characteristics. Preferably, a segmented liquid-crystal modulator selectively changes the polarization of the physically separated channels.

A first, polarization-sensitive embodiment is shown in cross-section in FIG. 1 in which a relatively broad-band input beam 10 strikes an entrance frequency-dispersive medium, such as a diffraction grating 12. It is assumed that the input beam 10 is polarized along the x-direction. Other active or passive dispersive media are possible, such as prisms. The frequency-dispersive medium 12 divides the broad-band input beam 10 into multiple frequency-separated input beams 14 and 16 which are spatially separated in the illustrated x-direction. An entrance lens 18 focuses the frequency-divided components upon separate segments 20 and 22 of a segmented liquid-crystal polarization modulator 24. An entrance polarization-dispersive element 26, such as a birefringent crystal, such as calcite, is disposed on the entrance side to spatially separate the different polarization components of the input beam, but its effects are not evident for the first embodiment from FIG. 1 because the input beam 10 is assumed to be linearly polarized along the x-axis.

The number of frequency-divided input beams 14 and 16 and the number of liquid-crystal segments 20 and 22 depend on the number of WDM components on the optical medium (optical fiber) which require switching. Four frequency sub-bands provide a meaningful telecommunication system. The segments 20 and 22 of the segmented liquid-crystal modulator 24 are separately controllable to change the polarization direction or other polarization characteristic of the physically separated frequency-divided input beams 14 and 16. In the simplest case, each segment 20 or 22 either linearly rotates the
polarization of the properly polarized frequency-separated input beam 14 or 16 by 90° or does not rotate the polarization. A twisted nematic liquid-crystal modulator provides such performance.

After traversing the liquid-crystal modulator 24, the frequency-separated beams 14 and 16 traverse the exit polarization-dispersive element 28, which, as additionally illustrated in FIG. 2, further separates the beams 14 and 16 into their respective polarization components 32, 34 and 36, 38. An exit lens 30 recollimates the beams. An exit frequency-dispersive medium 40, such as another grating, acts reciprocally to the entrance frequency-dispersive medium 123 and recombines frequency- and polarization-separated beams into only polarization-separated beams 42, 44, which, as will be shown later, are spatially separated as well.

Turning more completely now to the perpendicular illustration of FIG. 2, the two frequency beams 14 and 16 are congruent along the x-direction. It is assumed that the two input beams 14 and 16 are polarized along the x-direction and thus not affected by the entrance polarization-dispersive element 26. This assumption manifests that the system of FIGS. 1 and 2 is polarization sensitive. As a result, the entrance polarization-dispersive element 26 is not required for this polarization-sensitive, single-input embodiment.

Referring simultaneously to FIGS. 1 and 2 and to an isometric view, illustrated in FIG. 3, of the central portion of these figures, when the first segment 20 of the segmented liquid-crystal modulator 24 is not actively biased, it rotates by 90° the polarization of the incident beam 14 of the first frequency such that, when it traverses the output polarization-dispersive element 28, it is displaced downwardly along the y-axis into displaced output beam 34 of the first frequency. On the other hand, when the first segment 20 is actively biased, it does not rotate the polarization of the entrance beam 14 of the first frequency. As a result, it traverses the output polarization-dispersive element 28 without spatial displacement into undisplaced output beam 32 of the first frequency. Similarly, active biasing of the second segment 22 rotates by 90° the polarization of the entrance beam 16 of the second frequency, and thus the output polarization-dispersive element 28 converts it into displaced output beam 38 of the second frequency; while inactive biasing leaves its polarization unaffected, and thus the dispersive element 28 converts it into undisplaced output beam 36 of the second frequency. The output frequency-dispersive element 40 then
recombines the undisplaced output beams 32 and 36 of both frequencies into a combined undisplaced output beam 42 and the displaced output beams 34 and 38 of both frequencies into a combined displaced output beam 44.

Therefore, the biasing of both of the segments 20 and 22 of the liquid-crystal modulator 24 determines into which output beam 42 and 44 either or both of the entrance beams 14 and 16 are directed. That is, a polarization-sensitive 1×2 switch has been described.

Referring now to FIGS. 4, 5, and 6, a second input fiber outputs a second entrance beam 46, which strikes the entrance frequency-dispersive element 12 at a vertically oblique angle so as to produce from the second input fiber multiple angularly separated, frequency-separated beams 48 and 50. The second entrance beam is assumed to be polarized along the $y$-axis so that the entrance polarization-dispersive element 26 deflects it along the $y$-axis. The angular resolution of the input frequency-dispersive element 12 and birefringent length of the first polarization-dispersive element 26 are such that the components of the same frequency from the two input beams 10 and 46 are focused upon the same segment 20 or 22 of the segmented liquid-crystal modulator 24. As a result, the respective segmented polarization rotator of the liquid-crystal modulator 24 either rotates both the WDM components of the same frequency by the same polarization angle or does not. Preferably, the liquid-crystal modulator 24 rotates the polarization by 90° or does not rotate it. That is, either the linear polarization directions of either beam pair 14, 48 or 16, 50 are reversed or left intact (within an angular factor of 180°).

The second polarization-dispersive element 28 is oriented so as to act conversely to the first polarization-dispersive element 26. The beams 32 and 36 polarized along the $x$-axis remain undeflected, while the beams 34 and 38 polarized along the $y$-axis are deflected by the second polarization-dispersive element 28 back toward normal propagation path. The exit lens 30, however, angularly separates the resultant output beam 44 from the output beam 42.

In the parlance of a drop-add circuit, the input beam 10 is the IN channel, the input beam 46 is the ADD channel, the output beam 42 is the OUT channel, and the output beam 44 is the DROP channel.

By the means of the illustrated circuitry, the frequency-dedicated segment 20 or 22
of the liquid-crystal modulator 24 determines whether a pair of channels of the same
frequency on the two multi-frequency input fibers are to be switched to different output
fibers. Of course, the two segments 20 and 22 can be separately controlled for the two
frequency channels.

Although only two frequency channels have been described, it is understood that
more frequency channels can be accommodated by a liquid-crystal modulator 20 having
additional separately controlled segments along the x-direction.

The above embodiments are sensitive to polarization of their input signals. But, in
many cases, the input light polarization cannot be controlled. Merely using an input
polarizer is unsatisfactory because possibly all the light may be lost and because the
polarization state tends to be randomly vary in time, therefore leading to polarization-
cauased intensity fluctuations. However, the invention can be made to be polarization
insensitive.

As illustrated in FIG. 11, a first polarization-dispersive element 60, such as a
calcite crystal, divides an input beam 62 into two polarization-separated beams 64 and 66,
one the ordinary beam 64 and the other the extraordinary beam 66. One of the beams, in
the illustrated case, the extraordinary beam 66, passes through a polarization converter 68,
such as a half-wave plate which rotates the polarization by 90°, so that both beams 64 and
66 have the same well-defined polarization characteristic, here a linear polarization along
the x-axis. The entrance lens 18 focuses both beams 64 and 66 upon the same segment 20 or
22 of the liquid-crystal modulator 24, which simultaneously acts on both beams 64 and 66,
either leaving their polarization intact or rotating them or producing a combination
between beams. The exit polarization-dispersive element 28 then spatially separates them
according to polarization; if unrotated, into beams 80 and 82; if rotated, into beams 84 and
86. Two more polarization rotators 88 and 90 are disposed in two of the beams 82 and
84. The exit lens 30 recollimates the beams 80-86, and a second polarization-dispersive
element 92 acts conversely to the first one 60 to recombine the beams 80 and 82 into a
combined OUT beam 44 and to recombine the beams 84 and 86 into a combined DROP
beam 96.

The frequency-dispersed beams are not illustrated but are arranged similarly to
those of FIG. 4. The embodiment can be easily extended to a 2×2 drop-add circuit have an additional ADD input beam 98 by including a polarization rotator 100 for the added input on the entrance side.

The above embodiments have been described in somewhat theoretical terms. The following discussion involves some of the design considerations. Let \( f \) represent the focal lengths of the two lenses 18 and 30; \( d_1 \), the lateral shift of the inner polarization-dispersive elements 26 and 28; \( d_2 \), the lateral shift of the outer polarization-dispersive elements 60 and 92; and \( L \) the distance between the input polarization-dispersive element 60 and its associated lens 18. The switched (extraordinary beams) have a virtual focus shifted by \( d_1 \) from the ordinary focus. The extraordinary and ordinary beams therefore form an angle of \( d_1 / f \) with respect to the input and output ordinary beams. If \( f = 100 \) mm and \( d = 100 \) mm, the angle is 0.02 rad or about 1°. The main ordinary input beam is assumed to define \( x = 0 \) for each frequency. The ordinary beam is then at \( x = -d_2 \). The ordinary and extraordinary beams of the ADD (or DROP) channel at the lens 18 or 30 are located at \( x = d_1 \) and \( x = d_2 - d_1 \), respectively. At the external crystals, these beams are at \( x = ld_1/df - d_1 \) and \( x = ld_2/df - d_1 - s \).

For the beams to overlie at that point, it is required that \( L = f \).

The preceding embodiments have used a calcite crystal or similar uniaxial medium for the polarization-dispersive element. Wollaston prisms offer an advantageous alternative design. Such prisms have two prisms of calcite, for example, separated by a thin layer of material having a refractive index intermediate between the refractive indices of the ordinary and extraordinary refractive indices of the calcite. The two component prisms are oriented such that one of the rays is totally internally reflected by the intermediate thin layer. The result is that the ordinary and extraordinary rays are angularly separated.

A polarization-sensitive embodiment utilizing Wollaston prisms is illustrated in FIG. 12. The perpendicular construction is very similar to that of FIG. 4. The entrance and exit calcite crystals 26 and 28 of FIGS. 1, 2, and 3 are replaced by entrance and exit Wollaston prisms 110 and 112. Their birefringent thicknesses and the focal lengths of the two lenses 18 and 30 are arranged such that the two optical input beams 14 and 16, the IN and ADD beams, are focused to the interface of the entrance Wollaston prism 110 having
such a length that both beams 14 and 16 (of differing polarizations) then are congruent as
they pass the liquid-crystal modulator 24. Preferably, the input beams 14 and 16 can be
made parallel. Similar design factors on the output side allow the two output beams 42
and 44, the OUT and DROP beams, to be parallel.

Example 1

We have constructed and tested a switch according to the above embodiment. It
was designed to switch one or more of six channels having 4 nm spacing between the
channels and to have a wavelength resolution of 2 nm. The liquid-crystal modulator was
filled with commercially available E7 nematic liquid crystal and was twisted by 90°. The
polarization-dispersive element was a Wollaston prism. Many of the details of fabrication
are found in the parent patent application and the various cited patents to Patel. The
design of the switch was optimized for 1.5 µm. In an experimental prototype, we have
shown an extinction ratio of at least 35 dB between the switched and unswitched states of
the polarizers. In FIGS. 7 and 8 are shown the optical power spectra on the unswitched
output channel and the switched output channel respectively when no switching is
performed. That is, FIG. 8 shows the residual power in the four unswitched channels.
The power levels indicated on the vertical scale are somewhat arbitrary and reflect an 8 dB
system loss. In FIGS. 9 and 10 are shown the optical spectra of the unswitched and
switched outputs respectively when the first and third channels are switched. It is thus
seen that the inventive system effectively switches the WDM channels.

The embodiment of Wollaston prisms can be made insensitive to polarization, as
illustrated in FIG. 13, by including the first and second polarization-dispersive elements 60
and 92, preferably calcite crystals or similar material, on the input and output ends. Half-
wave plates 120, 122, and 124 are placed in the path of the laterally displaced beams and
in the path of both of the input ADD beams. The wide half-wave plate 124 causes the IN
and ADD beams to have differing polarizations as they congruently pass through a
segment of the liquid-crystal modulator 24. Similarly, half-wave plates 126, 128, and 130
are placed in the to-be-displaced output beams and both of the DROP beams.

The number of parts can be significantly reduced by using a reflector and operating
in the retro-reflector mode. As illustrated in FIG. 14, the input beam 14, after diffracting
from the grating (not shown), strikes the lens 18 off-center and is refracted obliquely to the principal optical axis. Because it is polarized along the x-direction, it passes undeflected through the polarization-dispersive element 26, which may be calcite or a Wollaston prism. It then passes through one segment of the segmented liquid-crystal polarization modulator system 140, which differs from the previously described liquid-crystal polarization modulators in that it selectively rotates the light polarization by 90° only after a double, back-and-forth pass. The light is then reflected from a mirror 142 and again traverses the polarization modulator 140. The polarization of light traversing actively biased segments of the modulator 140 is not rotated while that of light traversing inactively biased segments is rotated by a total of 90°. The light with rotated polarization is displaced by the polarization-dispersive element 26 and, after diffraction, is output as a first output beam 144 while the light with unrotated polarization is output as a second output beam 146. The two output beams 144 and 146 are angularly displaced so as to be easily separated physically.

The second input beam 46, assumed to be polarized along the y-direction strikes the lens 18 obliquely with respect to the first input beam 14 but in the same general off-axis location. Because of their assumed different polarizations, the polarization-dispersive element 26 affects them conversely, but the segmented polarization modulator 140 simultaneously rotates (or does not rotate) both of their polarization states. In the backward propagation, the diffraction grating recombines the optical frequency carriers into the desired ADD and DROP channels, as determined by the segmented polarization modulator 140.

The optical switch of FIG. 14 can be made frequency insensitive using techniques described for the other embodiments.

The frequency dispersion at the liquid-crystal modulator of the invention allows the modulator to simultaneously change the phase and/or amplitude of the different frequency components of the signals. Such adjustment is particularly advantageous to additionally compensate for the frequency dispersion of the optical fiber or to equalize amplitudes between different channels.

Although the described embodiments have placed the frequency-dispersive elements on the outside of the polarization-dispersive elements, it is recognized that the two
dispersions can be performed in the opposite order and even simultaneously.

The invention can thus be used in a number of related configurations, all of which are useful for providing an economical, all-optical multi-frequency switch. When the polarization modulator is a segmented liquid-crystal modulator, the system is both easy to construct, and the modulator has transfer characteristics consistent with a relaxed system design.
CLAIMS

What is claimed is:

1. An optical switch, comprising:
   a segmented polarization modulator having a plurality of polarization modulators
   arranged along a first axis and receiving a plurality of input optical beams and modulating
   polarization states of said optical beams; and
   a polarization-dispersive medium receiving outputs of said segmented polarization
   modulator and dispersing said outputs along an axis offset from said first axis according to
   polarization states of said outputs into a plurality of polarization-dispersed outputs

2. An optical switch according to Claim 1, further comprising:
   a first frequency-dispersive element receiving at least one first input signal and
   dispersing it into said at least one input optical beam according to frequencies thereof.

3. An optical switch according to Claim 2, further comprising:
   a second frequency-dispersive element receiving said dispersed outputs of said
   polarization-dispersive medium and combining frequency components thereof into a
   plurality of polarization-dispersed outputs.

4. An optical switch as recited in Claim 3, wherein said modulator is a liquid-
crystal modulator.

5. An optical switch, comprising:
   a first combination of a frequency-dispersive element and a polarization-dispersive
   element dividing a combined input beam into at least four frequency-dispersed and
   polarization-dispersed input beams spatially dispersed in two transverse directions;
   a segmented polarization modulator having multiple individually controlled
   segments receiving said at least four input beams for selectively controlling polarization
characteristics of said at least four input beams; and

a second combination of a frequency-dispersive element and a polarization-dispersive element receiving outputs of said polarization modulator and recombining them into combined output beams according to polarization and frequency.

6. An optical switch as recited in Claim 5:

wherein said first combination receives a second combined input beam of a plurality of frequency-divided optical signals;

wherein said modulator modulates both said first and second combined input beams; and

wherein said second combination combines components of said first and second combined input beams according to the polarization modulated upon them by said modulator.

7. An optical switch according to Claim 5, wherein said first combination receives a plurality of first input signals and disperses them into a plurality of input optical beams according to frequencies thereof.

8. An optical switch according to Claim 7, further comprising a second polarization-dispersive element receiving a second input signal and providing outputs to said first combination.

9. An optical switch according to Claim 8, further comprising a third polarization-dispersive element receiving outputs of said second combination and recombining them into respective wavelength-division multiplexed output beams.

10. An optical switch according to Claim 9, further comprising polarization rotators disposed in respective beams dispersed by said second polarization-dispersive element.

11. An optical switch according to Claim 5, wherein said polarization modulator
comprises a segmented liquid-crystal modulator.

12. An optical switch, comprising:
   a frequency-dispersive element receiving an input beam and dispersing it into a
   plurality of first beams according to frequency;
   a polarization-dispersive element receiving said first beams and outputting
   corresponding second beams;
   a segmented liquid-crystal polarization modulator receiving said second beams on
   respective segments thereof and selectively rotating polarizations thereof to form third
   beams; and
   a reflector reflecting said third beams back through said polarization modulator,
   said polarization-dispersive element, and said frequency-dispersive element.

13. A method of switching a wavelength-division multiplexed signal,
   comprising the steps of:
   frequency dividing an input wavelength-division multiplexed signal into frequency-
   divided components;
   selectively modulating according to polarization said frequency-divided
   components;
   polarization dividing said modulated frequency-divided components according to
   polarization states thereof into polarization-divided components; and
   recombining said polarization-divided components according to polarization.
FIG. 4

FIG. 5
FIG. 9

FIG. 10

6 / 9
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) : G02F 1/13, 1/03; H04J 14/06, 14/02; G02B 6/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/39, 94, 122, 124, 128, 245, 246, 494, 496, 615; 385/17, 37

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>JP 62-305152, (Nishio et al) 01 December 1987, see fig 1, pa. 6, lines 7-27. pa. 4 lines 5-11.</td>
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<td>Applied Optics, 01 June 1982, Shirasaki et al., Bistable Magnetooptic Switch For Multimode Optical Fiber, See entire document.</td>
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<td>US, A, 3,536,375, (Mansell) 27 October 1970 See entire document</td>
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