An apparatus for multiplexing or demultiplexing optical signals in an optical communication system includes a plurality of optical waveguides aligned generally along the same optical axis and having a propagating end. A reflective grating is optically coupled to the plurality of optical waveguides along the optical axis and has a surface receiving an optical signal emitted from at least one of the optical waveguides. The surface diffracts the optical signals into at least one other of the optical waveguides. A collimating/focusing optic having a select focal length is optically coupled between the plurality of optical waveguides and the reflective grating along the optical axis. The collimating/focusing optic is positioned relative to the propagating ends of the plurality of optical waveguides and the reflective echelle grating to propagate a telecentric optical beam(s) into the at least one other of the optical waveguides.
Fig. 18
(DE)MULTIPLEXER WITH FOUR 'F' CONFIGURATION AND HYBRID LENS

RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Patent Application Serial No. 60/272,748, filed Mar. 1, 2001, entitled “Echelle Grating (De)Multiplexer with Four ‘F’ Configuration and Hybrid Lens” and is a continuation-in-part application of U.S. patent application Ser. No. 09/628,774, filed Jul. 29, 2000, entitled “Echelle Grating Dense Wavelength Division Multiplexer/Demultiplexer.”

Dec. 5, 2002

[0002] The present invention relates generally to fiber-optic communications, and more particularly to bulk grating (de)multiplexers having a variable pass band and telecentricity.

BACKGROUND OF THE INVENTION

[0003] Described below with reference to FIGS. 1-6 is a bulk echelle grating DWDM device. One significant advantage of this echelle grating DWDM device is relatively high angular dispersion of the grating, enabling a (de)multiplexer having a compact footprint along the optical axis. However, this angular dispersion raises other design issues that inhibit efficient coupling of light from a fiber carrying a multichannel signal to an array of single channel fibers.

[0004] FIG. 16 is a schematic representation of an echelle grating (de)multiplexer 210, which is described in greater detail with reference to FIGS. 1-6 below. FIG. 16 includes only seven single channel output waveguides or fibers and these are shown equally spaced for ease of illustration. In fact, there can be forty or more single channel fibers associated with the multichannel fibers and the spacing between fibers may increase slightly from top to bottom. In a (de)multiplexing mode, light is emitted from a multi channel input fiber 212 (which typically is the first or last fiber in the plane of the single channel fiber array 220) forming a cone or beam of light 214 which is collimated by the lens 216 and directed on the reflective grating 218 which disperses the multichannel signal into its constituent channels according to wavelength. Thereafter single channel light reflected from the grating 218 is focused by the lens 216 to corresponding single channel output fibers 220. For channels which are directed to the most distal single channel fibers, for example fiber 222, the focused cone of light 224 has an “axis” 226 which is at a significant angle with respect to the face 228 of the distal fiber 222. Because light is coupled most efficiently to the output fibers along an axis perpendicular to the face 228, the greater the angle the axis 226 forms with respect to the face 228 the less efficient the coupling. Because of the relatively high angular dispersion of echelle gratings, the angle of the axis 226 in an echelle grating (de)multiplexer can be great enough to cause significant loss when coupling with the most distal output fiber 222.

[0005] The preferred way of addressing this problem is to provide a telecentric (de)multiplexer. “Telecentricity” is a property of the imaging system having effectively an exit pupil at an infinite distance such that the angle of the axis 226 is normal to the plane of the face 228 of the single channel fibers 220. A telecentric optical imaging system also ensures that the transmission efficiencies are the same in the multiplexing or demultiplexing mode of operation, i.e., a bidirectional device. One way to provide telecentricity is to replace the single lens 216 (or a two piece lens described below with reference to FIGS. 1-6) with a telecentric triplet lens. However, this requires the introduction of additional components which increases (de)multiplexer size, weight, complexity and cost.

[0006] One additional problem with the (de)multiplexer configuration illustrated in FIG. 1 is that the multichannel fiber 212 and the single channel fibers 220 have relatively narrow wavelength pass bands. The pass band is determined by the diameter of the cores of the optical fibers 212 and 220, and the spacing between adjacent fibers in array 220. This makes it difficult to provide for efficient coupling of light to the respective fibers, particularly for high speed data rates.

[0007] Martin, U.S. Pat. No. 6,084,695, describes a structure for widening the effective pass band of the fibers. In essence, Martin teaches providing a microlens array consisting of a gradient index lens (“GRIN”) microlens aligned with each fiber. Martin requires that the pitch between adjacent microlenses of the array be the same (within ±0.23 μm) as the pitch between corresponding adjacent optical fibers. Furthermore, because Martin teaches the use of GRIN microlenses, the structure taught by Martin requires that the face of the fibers be precisely at the focal plane of the microlenses of the array. The tight tolerances required by these alignment demands render the structure taught by Martin difficult and expensive to build, and subject to losses in efficient coupling due to any imperfections in component fabrication and changes in the alignment caused by environmental factors such as temperature changes, vibrations or the like. In addition, the structure of Martin does not allow for adjustability or tunability of the pass band. Furthermore, Martin fails to teach or suggest the advantages of a telecentric configuration.

[0008] A. W. Lohmann (1996) Optical Comm. 86:365, as well as S. Sinzinger and Jahans, “Microoptics” Wiley-VCH, p.215-217; 221-222 (1999) describe a 4F setup for imaging an input array into an output array and notes that the 4F imaging configuration is telecentric. In section 7.2.4 Sinzinger and Jahans describe hybrid imaging, which consists of imaging lenses in combination with an array of microlenses, with the microlenses reducing beam divergence, thus reducing the size and complexity of the conventional imaging lens. However, Lohmann, Sinzinger and Jahans were dis-
cussing optical cross connects and didn’t recognize the significant advantages the hybrid lens 4F configuration would have in combination with a reflective echelle grating (de)multiplexer and its high angular dispersion.

[0009] The present invention is directed toward overcoming one or more of the problems discussed above.

SUMMARY OF THE INVENTION

[0010] A first aspect of the present invention is an apparatus for multiplexing or demultiplexing optical signals in an optical communication system. The apparatus includes a plurality of optical waveguides aligned generally along the same optical axis each having a propagating end. A reflective grating is optically coupled to the plurality of optical waveguides along the optical axis and has a surface receiving an optical signal emitted from at least one of the optical waveguides. The surface diffracts the optical signals into at least one other of the optical waveguides. A collimating/focusing optic having a select focal length is optically coupled between the plurality of optical waveguides and the reflective grating along the optical axis. The collimating/focusing optic is positioned relative to the propagating ends of the plurality of optical waveguides and the reflective echelle grating to propagate a telecentric optical beam(s) into the at least one other of the optical waveguides. In one embodiment, the collimating/focusing optic is optically coupled to the propagating ends of the waveguide at about the select focal length from the collimating/focusing optic and on a point on the surface of the reflective echelle grating is spaced the selective focal length from the collimating/focusing optic. The reflective grating may be an echelle grating having a groove spacing of between about 50-300 grooves per millimeter and a blaze angle of between about 51-53 degrees. Another embodiment includes the combination of the telecentric (de)multiplexer and the array of microlenses combine all these advantages to result in a highly efficient (de)multiplexer which can be efficiently manufactured with significant cost savings over prior art devices.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is a schematic plan view of a multiplexer/demultiplexer using a bulk echelle grating in accordance with the present invention;

[0014] FIG. 2 is an enlarged cross-section of the echelle grating grooves illustrating relevant dimensions;

[0015] FIG. 3 is a graphical representation of possible step widths and riser heights at different orders which may yield a working echelle grating;

[0016] FIG. 4 is a schematic representation of an example of a multiplexer/demultiplexer with a bulk echelle grating in accordance with the present invention;

[0017] FIG. 5 is a partial cross-sectional view of a pigtail template;

[0018] FIG. 6 is a perspective view of the multiplexer/demultiplexer with bulk echelle grating of FIG. 1 illustrating the potential adjustment of the components;

[0019] FIG. 7 is a schematic view of a first alternate embodiment of the multiplexer/demultiplexer using a bulk echelle grating including a pair of collimating/focusing concave mirrors;
FIG. 8 is a second alternate embodiment of the multiplexer/demultiplexer of FIG. 7 further including a prism providing for wavelength dispersion in a horizontal direction;

FIG. 9 is a third alternate embodiment of the multiplexer/demultiplexer using a single collimating/focusing mirror;

FIG. 10 is a fourth alternate embodiment of the multiplexer/demultiplexer in accordance with the present invention using an off-axis parabolic mirror as the collimating/focusing optic with the device arranged in a near-littrow configuration;

FIG. 11 is a fifth alternate embodiment of the multiplexer/demultiplexer of the present invention using a concave echelle grating;

FIG. 12 is a schematic representation of an apparatus for dividing a broad bandwidth into bandwidth segments for multiplexing/demultiplexing;

FIG. 13 is a schematic representation of the embodiment of FIG. 12 using three waveband dividing elements; and

FIG. 14 is a schematic elevation of a pigtails harness having a one-dimensional input array of fibers and a two-dimensional output array of fibers;

FIG. 15 is a schematic representation of a multiplexer/demultiplexer having stacked multiplex fibers and a two-dimensional array of single channel fibers;

FIG. 16 is a schematic plan view of a prior art bulk optic multiplexer/demultiplexer;

FIG. 17 is a schematic plan view of a multiplexer/demultiplexer in a “4F” configuration in accordance with the present invention; and

FIG. 18 is a schematic plan view of a multiplexer/demultiplexer having a “4F” configuration and microlens array in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

A multiplexer/demultiplexer (a “(de)multiplexer”) for use in optical communication systems 10 of the present invention is illustrated schematically in FIG. 1. It includes a pigtails harness 12 consisting of an input waveguide 14, a plurality of output waveguides 16 arranged in a linear array adjacent the input fiber, a collimating/focusing lens 18 and an echelle grating 20, each of which are optically coupled. In the present discussion the (de)multiplexer will be discussed in terms of a demultiplexer. The description applies equally to a multiplexer, only with the function of the input and output waveguides 14, 16 reversed. Also, for the sake of clarity, only seven output waveguides are illustrated (the center output waveguides underlie the input fiber in FIG. 1 as can be seen with respect to elements 142 and 148 of FIG. 14). Furthermore, the waveguides 14, 16 are preferably single mode optical fibers. As will be discussed in greater detail below, in the preferred embodiment, 90 or more output waveguides can be associated with a single input waveguide, depending upon the bandwidth channel, separation and a number of other factors.

As used herein, “optically coupled” or “optically communicates” means any connection, coupling, link or the like, by which optical signals carried by one optical element are imparted to the “coupled” or “communicating” element. Such “optically communicating” devices are not necessarily directly connected to one another, but may be separated by a space through which the optical signals traverse or by intermediate optical components or devices.

As illustrated in FIG. 1, the (de)multiplexer 10 is in “near-littrow configuration,” meaning that the incident beam $\lambda_{1-n}$ and the channels diffracted off the surface of the grating $\lambda_{1-n}$, $\lambda_{1-n}$, $\lambda_{1-n}$, $\lambda_{1-n}$, $\lambda_{1-n}$, $\lambda_{1-n}$ are generally along the same optical axis (that is, they trace a very close path) and the lens both collimates the input beam $\lambda_{1-n}$ and focuses the diffracted channels $\lambda_{1-1}$ to the output fibers 16.

The echelle grating 20, like other gratings such as echelle grating, uses interference between light wavefronts reflected from various portions of its ruled surface or steps 22 to divide the incident beam consisting of a plurality of channels $\lambda_{1-n}$ having a select channel spacing within a select wavelength range $\lambda_{1-n}$ into separate channels of wavelength beams $\lambda_{1-1}$, which are angularly dispersed by the grating into output waveguides some distance away. Referring to FIG. 1, the channel separation of the device (D), which is the product of the focal length of the focusing/collimating optic the angular dispersion and the incremental channel spacing, is equal to the distance $S$ between the center of adjacent output waveguides. The echelle grating 20 is particularly suited to use in optical communication systems because of a unique combination of properties: 1) it provides clear channel separation notwithstanding channels being closely spaced (0.4 mm or less); 2) it provides large spatial separation of channels over relatively short distances; and 3) it is highly efficient in the range of optical communications wavelengths.

Referring to FIG. 2, for the purpose of this specification, echelle gratings are a special grating structure having groove density (1/d) of under 500 grooves/mm and a blaze angle $\beta$ of greater than 45° which typically operate at an order of diffraction greater than 1. In combination, these features enable a multiplexer/demultiplexer that efficiently separates closely spaced channels over a relatively small focal length (e.g., 5 inches) enabling a small form factor form factor (on the order of 10 inches in length or less).

Consideration of certain external and performance constraints point to the desirability of echelle gratings for DWDM. The external constraints include the following:

1) Minimize focal length, with a focal length of under 6 inches desired.

2) Center wavelength in near infrared, approximately at the center of the C-band, 1550 nm.

3) A minimal channel spacing (e.g., 0.4 nm or less).

4) Large free spectral range, 150 nm.

5) System f number in the range of 4-8.

6) Rugged, minimum cost system.
The performance constraints include:

1. Resolution greater than 20,000.
2. High dispersion.
3. Flat response across spectral range.
4. High efficiency or low loss, (>75%).
5. Minimize polarization dependent loss.

The external constraints of ruggedness size and cost minimization as well as performance constraints of ease of alignment and high efficiency dictate a litrow configuration, which simplifies the system optimization analysis.

FIG. 2 illustrates the echelle grating geometry and the variables set forth below.

- \( \theta_s = \text{blaze angle} \)
- \( \alpha = \text{incident angle} \)
- \( \beta = \text{diffracted angle} \)
- \( b = \text{step (reflective surface) size} \)
- \( d = \text{line/groove density} \)
- \( a = \text{riser size} \)

Examination of a number of constraining factors discussed above illustrate the utility of echelle gratings for DWDM.

1. Constraining Factors: \( f \) number \((f)\) in range of 4-8 and resolution \((R)\) > 20,000.

Result: For a grating in litrow configuration,

\[
R > 3 \left( \frac{W}{\lambda} \right).
\]

where \( W \) is the illuminated width of the grating. Thus, or \( W = (20,000/2)(1550 \text{ nm}) \) or \( W = 1.55 \text{ cm} \)

Result: For an echelle grating in litrow configuration,

\[
R = \frac{\lambda}{m},
\]

which implies

\[
m = 1550 \frac{10}{FSR}.
\]

or \( m \leq 10 \).

4. Constraining Factors: Wish to provide a flat response over the bandwidth.

Result: The diffraction envelope must have a broad enough maximum so that loss is minimized at the extremes of the wavelength range. This dictates \( b > 0.5 \mu \). An order over 7 spreads the light too much across the diffraction peak, resulting in unacceptably low efficiency. Thus: \( b > 0.5 \mu \) and \( m \leq 7 \).

5. Constraining Factors: High efficiency. (>85°)

Result: Efficiency is a function of step size. A step size must be selected providing a channel width capturing 90% of the signal at a select order. \( b > 3 \mu \) yields suitable efficiency.

6. Constraining Factors: Limitations on \( m \) from 4. and 2. above.

Result: 1.5 < \( m < 7 \).

7. Constraining Factors: For an echelle grating in litrow mode:

\[
a = \frac{m \lambda}{F}
\]

Result: \( a = \)

3.88\( \mu \) at \( m = 5 \)
4.65\( \mu \) at \( m = 6 \)
5.43\( \mu \) at \( m = 7 \)

FIG. 3 illustrates that these constraints and results provide a range of values for \( a \) and \( b \) at a given range of suitable orders \((m)\). Simulations aimed at maximizing efficiency and minimizing polarization dependent loss optimize around blaze angles and groove frequencies that fall in the range of echelle gratings, i.e., \( 45 < \theta_s < 78^\circ \) and \( d > 300 \) grooves/mm. Furthermore, limitations on manufacturing further dictate that only echelle gratings can provide the necessary results within the external and performance constraints.

In designing a functioning (dc) multiplexer, a number of design parameters were selected that were dictated by many of the external and performance constraints set forth
above. An exemplary configuration is illustrated schematically in FIG. 4, with like elements having the same reference number as FIG. 1. The dictating constraints and their effect on the exemplary bulk echelle grating DWDM are as follows:

[0084] 1. Channel Characteristics

[0085] Currently optical communications utilize what is known as the “C” band of near infrared wavelengths, a wavelength band ranging from 1528-1565 nanometers (nm). This provides a bandwidth or free spectral range of 37 nm available for channel separation. Known prior art (de)multiplexers require a channel spacing of 0.8 nm or even 1.6 nm, resulting in a possibility of only between 48 and 24 channels. Because echelle gratings provide markedly superior channel dispersion, a much smaller channel spacing of 0.4 nm was chosen, resulting in a possibility of 93 channels over the C band. As the tuning range of semiconductor lasers increases and optical communications expand beyond the “C” band to include the “L” band (1566-1610 nm) and the “S” band (1490-1527 nm), a total bandwidth of about 120 nm or more is foreseeable, creating a possibility of the (de)multiplexing accommodating 300 channels or more per input fiber.

[0086] Current optical communications operate primarily at a channel frequency of 2.5 GHz, known as OC48. At OC48 the channel width \( \lambda_{\text{oc}} = 0.02 \) nm. Optical communications are currently beginning to adopt a frequency of 10 GHz, known as OC192. At OC192 the channel width \( \lambda_{\text{oc}} = 0.08 \) nm.

[0087] 2. Fiber Dimensions

[0088] Standard single mode optical fiber used in optical communications typically have an outer diameter of 125 microns (\( \mu \)) and a core diameter of 10\( \mu \). Optical fibers having an outer diameter of 80\( \mu \) and core diameter of 8.3\( \mu \) are available, model SM-1250 manufactured by Fibercore. In this example, both the input fiber 14 and the output fiber 16 are single mode and share the 80\( \mu \) outer diameter. Assuming the output fibers 16 are abutted in parallel as illustrated in FIG. 4, this results in the core centers being spaced 80\( \mu \), or a required channel separation D of 80\( \mu \) at the select focal length. Because fibers of different outer diameter are available and fibers cladding can be etched away, it is possible that the 80\( \mu \) spacing can be reduced, with core spacing of 40\( \mu \) or less being foreseeable, which could enable shorter focal lengths or different echelle grating designs having lesser angular dispersion. The spread of the beam emitted from the fiber was 10° at the e-folding distance, although it was later found to be 14° at the 1% point.

[0089] 3. Form Factor

[0090] The design was intended to provide a high channel density in a form factor consistent with or smaller than used in current (de)multiplexer devices. A total length of between 10-12 inches was the design target. To accommodate all the optics and harnesses, a maximum focal length of 5 inches (127 mm) was chosen. As discussed above, in light of the constraining factors of the f number between 4-8 and a resolution (R)>20,000, a focal length of 124 was ultimately dictated.

[0091] 4. Dispersion Limitations

[0092] In order to prevent the loss of data, it was necessary that the dispersion of the echelle grating be constrained. The initial 0.4 nm channel spacing at the echelle grating was required to be about 80\( \mu \) of separation at the output fibers (corresponding to the core spacing). On the other hand, the 0.08 nm channel width of OC192 frequencies could not disperse to much greater than the fiber core aperture over the focal length. Thus:

\[
\frac{\text{channel separation}}{\text{fiber spacing}} < \frac{0.4 \text{ nm}}{80 \mu}
\]

while

\[
\frac{\text{channel width (OC192)}}{\text{core diameter}} > \frac{0.08 \text{ nm}}{8.3 \mu}
\]

[0093] 5. Grating Design

[0094] The variables affecting grating design are:

[0095] 1) wavelength range

[0096] 2) efficiency

[0097] 3) dispersion (D)

[0098] 4) desired resolution

\[
\left( \frac{\lambda}{\Delta \lambda} \right)
\]

[0099] FIG. 3 is a cross-section showing the principle echelle grating dimensions including: blaze angle (\( \theta_b \)), wavelength range and groove density (d).

[0100] For design of the grating, 150 channels centered on 1550 nm was chosen. This results in a physical size of the spectral image of (number of channels)x(maximum separation, or 150x80u)=12,000u. This desire to have 90% of the intensity contained in 12,000\( \mu \) constrains the size of b. The far field pattern of the diffraction grating is

\[
l = \left( \frac{\sin \beta}{\beta} \right) \left( \frac{\sin \frac{\theta}{2}}{\frac{\theta}{2}} \right) ^2 .
\]

[0101] N=number of lines illuminated,

\[
\beta = \frac{\pi b}{\lambda} \sin \theta_b
\]

[0102] and

\[
a = \frac{\pi d}{\lambda} \sin \theta_b
\]

[0103] Spreadsheet calculations show that b<5.5\( \mu \) (or b<8.5\( \mu \)) is necessary to make the spectral image>12,000\( \mu \)
at its 90% intensity point. To minimize loss, i.e., maintain adequate efficiency, \( b > 2 \lambda \). Thus, \( 2 \lambda < b < 5.5 \lambda \). (Condition A).

**[0104]** In Littrow mode, the angular dispersion is:

\[
\frac{d\theta}{d\lambda} = \frac{m}{d \cos \theta}, \quad \frac{d\theta}{d\lambda} = \frac{m}{b}
\]

\[\Delta \lambda \text{ (linear separation)} = \frac{m}{b} \left( 4 \times 10^{-4} \mu / (1.2 \times 10^2 \mu) \right)
\]

\[80 \mu < \frac{m}{b} \left( 4 \times 10^{-4} \mu / (1.2 \times 10^2 \mu) \right)
\]

\[m > \frac{1.6b}{\theta_0} > 1.6b \mu
\]

**[0105]** However, for OC192, dispersion must be constrained to contain the 0.08 nm channel width in a 10 \( \mu \) core, so that \( m > 3.34 \mu \).

**[0106]** Thus, \( 1.67b \mu < m < 3.34b \mu \) (Condition B).

**[0107]** The desired resolution

\[R = \frac{1}{\Delta \lambda} = N \cdot m.
\]

**[0108]** Here, \( \lambda = 1550 \text{ nm} \) and \( \Delta \lambda = 0.08 \text{ nm} \), yielding a required resolution \( R = 19,375 \) or approximately 20,000. Assuming a beam size at the grating of 2.1 cm (based upon a \( \Psi = 124 \text{ cm} \) and 10\(^\circ\) divergence):

\[N = \frac{m^2 (1.1)}{\cos \theta_0} = \frac{p}{\text{lines/cm}} = \frac{1}{d}
\]

**[0109]** Thus,

\[20,000 < \frac{2.1 \times 10^{-2} \text{ cm}}{d \cos \theta} \cdot m = \frac{2.1 \times 10^{-2} \text{ cm}}{b \cdot m}
\]

**[0110]** or \( b < 1.05 \text{ m} \) (Condition C).

**[0111]** To align the order \( m \) with the diffraction peak in Littrow mode, we know

\[a = \frac{m \lambda}{2}
\]

**[0112]** or a must have the values:

- \( a = 3.88 \mu \) at \( m = 5 \)
- \( a = 4.65 \mu \) at \( m = 6 \)
- \( a = 5.43 \mu \) at \( m = 7 \) (Condition D)

**[0113]** Only as \( \theta_0 \) increases to greater than 45° is it possible for conditions A and D to be satisfied. Assuming \( \theta_0 = 60\text{°} \), and \( m = 5 \),

**[0114]** \( a = 3.38 \mu \)

**[0115]** \( b = 2.24 \mu \)

**[0116]** \( d = 4.48 \mu \)

**[0117]** All of conditions A-D are satisfied.

**[0118]** Selection of the precise groove density and blaze angle are also affected by the polarization dependent loss and manufacturing constraints. For the embodiment illustrated in FIG. 4 use of an interferometrically controlled ruling engine to machine the line grating drove the selection of a line density evenly divisible by 3600. Considering these various factors led to selection of groove density \( d = 171.4 \text{ grooves/mm} \) and \( m = 5 \). This leads to \( a = 3.88 \mu \), \( b = 3.55 \mu \), and a corresponding blaze angle of 52.6° for this example. However, this methodology shows that for a focal length between 30-125 mm and an order of 5-7, potential blaze angles range between 51° and 53° and the groove density carries between 50 and 300 grooves/mm to provide linear channel separation of between 40-125 microns and an angular dispersion of the echelle of between 0.091 and 0.11 degrees/mm.

**[0119]** In the example of FIG. 4, the echelle grating has a groove density of 171.4 grooves/mm and a blaze angle of 52.6°. The echelle may be formed from one of several known methods. For example, it may be formed from an epoxy layer deposited on a glass substrate into which a master die defining the steps is pressed. The steps are then coated with a highly reflective material such as gold. The steps may also be precision machined directly into a glass or silicon substrate and then coated with a reflective material. A further option is the use of photolithographic techniques described in McMahon, U.S. Pat. No. 4,736,360, the contents of which are hereby expressly incorporated by reference in its entirety.

**[0120]** The lens 18 could be a graded index (GRIN) optic with spherical surfaces or a compound lens with one or more surfaces that might not be spherical (aspheric). The use of lenses or a single lens to collimate the beam and focus the dispersed light limits spherical aberrations or coma resulting from the use of front surface reflectors that require the optical rays to traverse the system in an off-axis geometry. A first type of potential lens uses a radially graded refractive index to achieve near-diffraction limited imaging of off-axis rays. A second type of lens actually consists of at least two individual pieces cemented together (doublet). Another option uses three individual lens pieces (triplet). These pieces may individually have spherical surfaces, or if required for correction of certain types of aberration, aspheric surfaces can be utilized. In this case, the lens would be referred to as an aspheric doublet or triplet.

**[0121]** In the example illustrated in FIG. 4, the lens 18 is an aspheric singlet of a 25.4 mm diameter having a spherical surface 26 with a radius of curvature of 373.94 mm and an aspheric surface 28 with a radius of curvature of 75 mm and a conic constant of -0.875. The average focal length in the 1520-1580 nm wavelength range is 125.01 mm. Thus, the distance \( A \) from the center of the spheric surface to the emitting end of the input and output fibers 14, 16 is about 125 mm. The average distance between the aspheric surface 28 and the center of the surface of the grating 20 is about 43.2 mm.
In the pigtail 12 of FIG. 1, the input and output fibers terminate in the same plane. This is also the case with the example illustrated in FIG. 4. In some configurations, however, the inlet 14 and outlet fibers 16 are on slightly different axes and do not terminate in the same plane. The fibers 14, 16 of the pigtail are precisely located by being fit into a template 34 illustrated schematically in FIG. 5. The template 34 has a plurality of parallel v-shaped grooves 36. The template and v-shaped grooves are preferably formed by etching the grooves 36 into a silicon substrate. In the example in FIG. 4, the grooves of the template are spaced 80μ.

The example configuration of FIG. 4 is shown in perspective view in FIG. 6. To facilitate alignment, the pigtail 12, the lens 18 and the grating 20 have limited freedom of movement in multiple directions. Once they are moved into position, they are secured in place by clamps or a suitable bonding agent. The lens 18 is held stationary. The pigtail 12 is movable by translation along the x, y and z axes. The input and output fibers can be moved independently along the x axis. The echelle grating 20 is fixed against translational movement except along the z axis. It can be rotated about each of the x, y and z axes. Other possible combinations of element movement may also yield suitable alignment.

The dimensions and performance criterion of the DWDM device 10 of FIG. 4 are summarized as follows:

- Fibers: SM-1250 (Fibercore) outer diameter 80μ
- Outer diameter: 80μ
- Core diameter: 8.3μ
- f Number: 4-8
- Lens: Aspheric singlet
- Average focal length (f)=125
- Optical Signal: λ=1528-1565 nm channel spacing=0.4 nm
- Grating:
  - d=5.83μ
  - θ=52.6°
  - order=6
- System Performance:
  - D (linear separation)=80μ
  - Resolution (R)=20,000
  - Efficiency=75%
- As an alternative to the use of a littrow configuration as well as the use of collimating lenses, concave mirrors may be used for collimating and focusing the incident beam. A first alternate embodiment of a concave mirror dense wavelength (de) multiplexer 40 is shown schematically in FIG. 7. Single mode input fiber 42 emits a divergent incident beam 44 consisting of multiplexed channels onto the surface of a collimating focusing concave mirror 46. The collimated beam 48 is then directed in an off-axis manner to the surface of an echelle grating 50. The echelle grating disperses the channels according to their wavelength in the manner discussed above with respect to FIGS. 1 and 4 and the dispersed channels 52 are reflected off axis off the front surface of the concave collimating/focusing mirror 54. The collimating/focusing mirror 54 then focuses and reflects the various channels to a corresponding fiber of an output fiber array 56. As alluded to above with respect to the discussion of the embodiments of FIGS. 1 and 4, use of surface reflecting optics such as the collimating mirror 46 and the concave focusing mirror 54 requires that the optical beams traverse the system in an off-axis geometry which creates significant aberrations (spherical aberrations and coma) that significantly limit the performance of the system. However, the use of the front surface reflecting optics has the potential of facilitating a more compact form factor than is possible with littrow configurations using a single optical lens. As should be readily apparent, combinations of front surface reflecting optics and lenses can be used in non-littrow configurations where necessary to balance form factor minimization requirements and optical aberrations.
- A second alternate embodiment 60 is illustrated in FIG. 8 which is a schematic representation of an echelle grating (de) multiplexer using a prism in combination with front surface optical mirrors. In this embodiment, light from a single mode input fiber 62 is directed off a collimating/focusing mirror 64 and the collimated beam 66 is directed through prism 68. The prism 68 provides for wavelength dispersion in a horizontal direction as indicated by the beams 70. These horizontally dispersed beams 70 are directed off the echelle grating 72 which in turn diffracts the beams 70 in an orthogonal dimension and directs these diffracted beams off the front surface of the concave collimating/focusing mirror 74. A two dimensional output fiber array 76 receives the focused beams from the collimating/focusing mirror 74. The use of the prism 68 in combination with the echelle grating 72 provides a two dimensional array of wavelength dispersion and may therefore facilitate detector arrays of shorter length as may be desirable in certain applications.
- FIG. 9 is a schematic representation of a third alternate embodiment 80 using a single concave mirror as both a collimating and focusing optic along the optical axis. In this embodiment, input fiber 82 directs a beam consisting of multiplexed channels to the surface of the concave mirror 84. A collimated beam 86 is reflected off the echelle grating 88 which diffracts the multiplexed signal in the manner discussed above. The multiplexed channels are then reflected off the surface of the concave mirror 84 and directed into the array of output fibers 92. While the embodiment 80 contemplates the mirror 84 being spherical and therefore having a constant diameter of, for example 25 cm, a slightly parabolic or aspheric mirror may be used to improve image quality, if necessary.
- FIG. 10 is a fourth alternate embodiment 100 using an off-axis parabolic mirror as the collimating/focusing optic. In this embodiment, multiplexed light from the input fiber 102 is directed off the front surface of an off-axis parabolic mirror 104 which in turn directs a collimated beam of light 106 off the surface of an echelle grating 108. The multiplexed light is reflected off the surface of the echelle grating 108 back to the surface of the off-axis parabolic mirror 104 and dispersed to respective output fibers 106. In this embodiment, the echelle grating is in near-littrow configuration, thereby directing light back to the output fibers 106.
A fifth alternate embodiment illustrated in FIG. 11 uses a concave echelle grating 107 configured to be the optic which collimates and focuses the incoming beam. This embodiment eliminates the need for the collimating/focusing lenses or concave mirrors of alternate embodiments one-four.

Various modifications can be provided to the basic echelle grating (de)multiplexer structures illustrated schematically in FIGS. 1-11 to further increase the channel carrying capacity of single mode optical fibers. As alluded to above, it is foreseeable in the future that advancements in optical amplifier technology will enable bandwidth in excess of the current 60-80 nm bandwidth used in optical communication. Such broad bandwidths tax the ability of an echelle grating DWDM to effectively multiplex and demultiplex the entire bandwidth, particularly in the frequencies at the edge of this broad band. Accordingly, it would be useful and desirable to use a network of echelle grating DWDM devices with each device optimized to multiplex/demultiplex light in a portion of the broad spectral range. For example, assuming future amplifier technologies enable bandwidths on the order of 120-180 nm, each echelle grating DWDM could be optimized to function with a portion, for example 1/2, of the bandwidth, 60-90 nm.

FIG. 12 illustrates schematically an apparatus 110 for dividing a broad bandwidth for (de)multiplexer. The apparatus 110 consists of an input fiber 112, a high pass thin film filter 114, a first focusing lens 116, a second focusing lens 118, a first echelle grating DWDM device 120 and a second echelle DWDM device 122.

By way of example, the operation of the apparatus for dividing broad band signals 110 will be discussed in terms of a demultiplexer. As with other embodiments of this invention, the apparatus may likewise function as a multiplexer simply by reversing the direction of light propagation. A multiplexed beam 124 emitted from the input fiber 112 is directed onto the high pass thin film filter 114. The high pass thin film filter has a design cut off wavelength that reflects the lower half of the wavelength range toward the first echelle grating DWDM 120. The upper half of the wavelength range passes through the filter 114 to the second echelle DWDM device 122. In this example, the input wavelength is in the range of 1460-1580 nm. The high pass thin film filter is designed to cut the band at 1520 nm. Thus, a wavelength range of 1460-1520 nm is directed toward the first echelle grating DWDM and a wavelength band of 1520-1580 nm is directed toward a second echelle grating DWDM device. The signal directed toward the first echelle grating DWDM is optically coupled to the first focusing lens 116 which directs the lower wavelength beam as an input to the first echelle grating DWDM. In a like manner, the upper wavelength beam 128 is optically coupled to the second focusing lens 118 which focuses the upper wavelength beam 128 as an input beam to the second echelle DWDM device 122.

The present example contemplates the use of a high pass thin film filter 114. However, other waveband dividing elements could be used instead, including devices using fiber Bragg gratings.

The first and second echelle grating DWDM devices 120, 122 of the present invention could have any of the configurations discussed above with regard to FIGS. 1-11. The use of the echelle DWDM devices for demultiplexing the split wavelength bands provide the many advantages discussed above with regard to the embodiments illustrated in FIGS. 1-11. However, the present invention could be practiced with other DWDM devices such as fiber Bragg grating devices, integrated waveguide arrays or the like. With an echelle spectrograph permitting wavelength spacing of 0.4 nm, a device for providing a total wavelength range of 120 nm will allow up to 300 channels to be demultiplexed from a single fiber. Furthermore, this system is scalable. FIG. 13 illustrates schematically how an input bandwidth of 1460-1700 nm can be divided using three wavelength dividing elements to four 60 nm bandwidth beams each of which can be input into an optimized echelle grating DWDM device. Such a device is capable of accommodating a total waveband of 240 nm and assuming a wavelength spacing of 0.4 nm, a total channel count of 600.

The bulk optic echelle DWDM of the present invention is able to simultaneously demultiplex signals from a number of input fibers. In each of the echelle grating DWDM devices illustrated in FIGS. 1-7 and 9-11 above, light is spatially resolved in only one dimension, vertically in a direction transverse the dispersion direction. As a result, input fibers can be vertically stacked in a linear array and a corresponding two dimensional array of output fibers can be provided for receiving demultiplexed signals from the various input fibers. This concept is illustrated schematically in FIG. 14. FIG. 14 is an elevation view of a pigtail harness 140 from the direction of the collimating/focusing optic. First, second and third input fibers 142, 144, 146 lying in a vertical linear array are optically coupled to first, second and third horizontal output rows 148, 150, 152, respectively. Thus, a one dimensional input array produces a two-dimensional output array. While the present example is limited to three input fibers 142, 144, 146 and only nine output fibers in the output first, second and third output rows 148, 150, 152, the actual number of output fibers will correspond to the number of input channels and will be a function of the channel separation and input bandwidth, and may easily exceed 90 output fibers per output fiber row. Each output fiber has a core center, and the output fiber core centers are spaced a distance equal to the linear separation of the grating at the device focal length. Further, the number of corresponding input and output arrays may be greater than three and is largely a function of external factors such as the space available for the pigtail harness 140. As should be appreciated, this configuration allows a single demultiplexer to demultiplex channels from a number of input fibers, thereby minimizing the number of echelle grating DWDM devices required for a multiple input fiber optical system. This further illustrates the flexibility and scalability of the echelle grating DWDM devices in accordance with the invention.

FIG. 15 is a schematic representation of a preferred embodiment of a stacked input bulk optic echelle DWDM device 160. Input beam λ3,10 from input fiber 142 is directed to the collimating/focusing optic 162 and a collimated beam is then directed off the reflective surface of the reflective echelle grating 164. The diffracted channels λ1,3 then return through the collimating/focusing optic 162 and are dispersed to the fibers comprising the first output row 148 as illustrated by λ1,3. The collimating/focusing optic has an optical axis 166 and the input fiber 142 and the output row 148 are equally spaced from the optical axis 166 of the collimating/focusing optic in the vertical direction. In a like
manner, a multiplexed input beam $\lambda_{2,\ldots,n}$ is emitted from the input fiber 144 and its various channels $\lambda_{1,\ldots,n}$, $\lambda_{2,\ldots,n}$ are diffracted to the second horizontal output row 150. With respect to each of output rows 148 and 150, the centers of the optical fibers in the row are spaced a distance from the centers of adjacent optical fibers in the row equal to the channel separation of the echelle grating 164 at the focal length of the collimating/focusing optic 162. The propagating ends of the output fibers as well as the propagating ends of the input fibers all lie in a plane spaced the focal length of the collimating/focusing optic from the collimating/focusing optic.

[0152] The echelle grating DWDM devices in accordance with the present invention provide for dense channel spacing (0.4 mm) over a given bandwidth, thereby maximizing the number of channels that can be carried by a single fiber for a given bandwidth. By careful selection of the echelle grating blaze angle and step spacing, the channels may be multiplexed/de-multiplexed at high resolutions and high efficiencies. Further, use of the echelle grating enables a smaller form factor because the angular diffraction allows for shorter focal lengths between the focusing lens and the input/output fibers. The use of bulk optical elements provides a system which is easy to manufacture, highly reliable and scalable. Further embodiments of the invention including the use of a waveband dividing element such as a thin film high pass filter allows extremely broad bands of signals to be divided and simultaneously multiplexed or de-multiplexed in parallel. Because the device disperses light in a single linear dimension, a plurality of input fibers can be stacked so that each bulk optic echelle grating DWDM device can accommodate multiple input fibers.

[0153] FIG. 17 is a schematic representation of a telecentric (de)multiplexer 230 in accordance with the present invention. The elements of FIG. 17 which are identical to those of FIG. 16 will have the same reference number followed by a prime (e.g., 16'). As with FIG. 16, only a few equally spaced single channel fibers are included for simplicity. In the embodiment of FIG. 17, the grating 18 is situated so that center 231 of its reflective surface is located at the focal distance $F$ of lens 16. The array of single channel fibers 220 is situated with the faces 228 at or near the focal plane 223 located at the focal length $F$ from the lens 216. As used herein, “at or near the focal plane” means located physically at or close enough to the focal plane that any performance degradation resulting from not being at the focal plane is inconsequential. Because the grating 218 is reflective, this configuration produces a 4F configuration as between the microlens array 220, the lens 216 and the grating 218. The 4F configuration results in a telecentric optical beam being propagated to the distal fiber 222. In other words, the axis 226 is substantially normal to the face 228 of the distal fiber 222. Likewise, the other single channel fibers 220 receive a telecentric beam; that is, the axis of their incident beams are essentially perpendicular to their face.

[0154] FIG. 18 is another embodiment of a (de)multiplexer 240. Elements of FIG. 18 which are identical to those of FIG. 16 have the same reference number followed by a double prime (e.g., 16''). Like FIG. 16, only a few equally spaced single channel fibers are included for simplicity. A microlens array 242 is situated at or near the focal plane 243 of the lens 16. The grating 218 is situated so that the center 244 of its reflective surface is located at the focal distance $F$ of lens 216 opposite the microlens array 242. Because the grating 218 is reflective, this configuration has essentially a 4F configuration as between the microlens array 242, the lens 216 and the grating 218, resulting in a telecentric (de)multiplexer.

[0155] Each lens 246 of the microlens array has a diameter ‘D’ which is significantly greater than the diameter ‘d’ of the core 248 of the single channel fibers. As known in the art (see Chamberlin and Hill, “Designs for High Channel Density Single-Mode Wavelength-Division-Multiplexers,” Proceedings of the SPIE, Vol. 839 (p. 60-66) (1987)) this has the effect of broadening the pass band so as to improve coupling with the fibers. In addition, the 4F configuration illustrated in FIG. 18 makes the (de)multiplexer telecentric. As a result, light from the microlens array 246 strikes the face 228 of the fiber cores essentially perpendicular to the plane of the face. This not only improves the coupling efficiency, but allows for greater tolerances in alignment of the optical axis of the fiber cores with the optical axis of the microlenses making up the microlens array. As a result, limited fabrication and environmentally caused differences between pitch ‘P’ between the optical axis 250 of adjacent microlenses and the pitch ‘p’ between the optical axis 252 of corresponding adjacent single channel fibers 220 will not affect the performance of the device.

[0156] One important benefit of this configuration is that the device size, that is, length along the optical axis, can be reduced significantly because the beam divergence of the input light has greatly decreased by the microlenses array 242. As a result, free space diffraction grating based (de)multiplexers can be made comparable in physical dimensions to that based on the planar Planoz Lightwave circuits.

[0157] Each of the microlenses 246 which constitute the microlens array 242 is a conventional plano-convex spherical refractive lens. The input plane of the fiber faces 228 can be situated such that the focal point of the lenses 246 is at the face 228 as illustrated at 254 or within the fiber core some distance as illustrated at 256 and 258. This feature further gives adjustability on pass band broadening. The tunability of the pass-band broadening permits optimizing of the pass band without introducing unacceptable cross talk. The telecentricity of the 4F system further increases the range of tunability. Finally, the feature provides for greater tolerances in alignment of the fibers along the optical axis of the (de)multiplexer.

[0158] In the preferred embodiment, the grating 218 is an echelle grating in accordance with the invention described above with reference to FIGS. 1-6. Because of the enhanced angular dispersion of the echelle grating, the telecentricity of the configurations illustrated in FIGS. 17 and 18 is of enhanced significance. That is, the 4F configuration provides telecentricity which provides an efficient coupling with the fiber cores which cannot be achieved absent telecentricity because of the steep angular dispersion of the echelle gratings, particularly at the extreme ends of the fiber array. As further discussed above, the telecentricity further allows finite differences between the pitch ‘P’ between adjacent lenses of the microlens array and the pitch ‘p’ between the optical axis of corresponding adjacent fibers. Thus, the pitch can be intentionally offset and/or the pitches can be set to much greater fabrication tolerances than prior art devices.
Furthermore, use of refractive plano-convex spherical lenses 246 in the microlens array of the embodiment of FIG. 18 simplifies the fabrication of the microlens array and also allows for the focal point to extend varying distances within the core of the single channel fibers without effecting coupling efficiency, a significant advantage over the teachings of Martin. This further provides for a greater tolerance in alignment along the optical axis of the (de)multiplexer and tunability in pass band broadening. Moreover, the telecentricity enhances the range within which the pass band can be tuned.

[0159] The specific design parameters such as the focal length and diameter of the imaging lens and the microlenses will be a factor of the size requirements, grating properties, input channel spacing, single channel core diameter and core spacing, and wavelength of the optical signal among other factors known in the art. Representative microlenses used with an echelle grating of the type described with respect to FIGS. 1-6 with an optical signal having a wavelength of 1528-1565 nm and a 0.8 nm channel spacing would be a plano-convex lens having a focal length on the order of 300 microns and a diameter of about 80 microns and a representative imaging lens would be a spherical cemented doublet with a focal length of about 65 mm and a diameter of about 10 mm.

1. An apparatus for use in optical communication systems to multiplex or demultiplex an optical signal, the apparatus comprising:
   a plurality of optical waveguides aligned generally along the same optical axis each having a propagating end;
   a reflective grating optically coupled to the plurality of optical waveguides along the optical axis having a surface receiving an optical signal emitted from the propagating end of at least one of the optical waveguides and diffracting the optical signal(s) into the propagating end of at least one other of the optical waveguides; and
   a collimating/focusing optic having a select focal length optically coupled between the propagating ends of the plurality of optical waveguides and the reflective grating along the optical axis, the collimating/focusing optic being positioned relative to the propagating ends of the plurality of optical waveguides and the reflective grating to propagate a telecentric optical beam(s) into the at least one other of the optical waveguides.

2. The apparatus of claim 1 wherein the collimating/focusing optic is positioned with the propagating ends of the waveguides about the select focal length from the collimating/focusing optic and a point on the surface of the reflective echelle grating being spaced the select focal length from the collimating/focusing optic.

3. The apparatus of claim 1 wherein the plurality of optical waveguides comprise at least one multiplex waveguide propagating a plurality of multiplexed channels and the others of the optical waveguides are single channel waveguides propagating single channels, the single channel optical waveguides being in a linear array, the apparatus further comprising:
   a linear array of microlenses with a microlens optically coupled to each single channel waveguide, the micro-
   lens array residing between the propagating end of the single channel waveguides and the collimating/focusing optic.

4. The apparatus of claim 3 wherein the linear array of microlenses is located at about a focal plane spaced about the select focal length from the collimating/focusing optic.

5. The apparatus of claim 1 wherein the reflective grating is an echelle grating having a groove spacing of between about 50-300 grooves per millimeter and a blaze angle of between about 51-53 degrees.

6. The apparatus of claim 1 wherein the reflective grating is an echelle grating having a groove spacing of between about 50-300 grooves per millimeter and a blaze angle providing an angular dispersion of about 0.091 and 0.11 degrees per nanometer for a select order of diffraction of between 4-7.

7. The apparatus of claim 4 wherein at least one microlens is in a corresponding waveguide.

8. The apparatus of claim 4 wherein the focal point of at least one microlens is at the propagating end of a corresponding waveguide.

9. An apparatus for use in optical communication systems to multiplex or demultiplex an optical signal, the apparatus comprising:
   a plurality of optical waveguides aligned generally along the same optical axis each having a propagating end, the plurality of optical waveguides including at least one multiplex waveguide propagating a plurality of multiplexed channels and the others of the optical waveguides being single channel waveguides propagating single channels;
   a reflective grating optically coupled with the plurality of optical waveguides along the optical axis having a reflective surface receiving an optical signal emitted from at least one of the optical waveguides and diffracting the optical signal(s) into at least one other of the optical waveguides;
   a collimating/focusing optic having a select focal length optically coupled between the propagating ends of the plurality of optical waveguides and the reflective surface of the echelle grating along the optical axis, the reflective surface of the echelle grating being spaced about the select focal length from the collimating/focusing optic; and
   an array of microlenses residing in optical communication between the propagating end of the single channel waveguides and the collimating/focusing optic, the array of microlenses being positioned relative to the collimating/focusing optic to propagate a telecentric optical beam(s) into the at least one other of the optical waveguides.

10. The apparatus of claim 9 wherein the single channel optical waveguides are in a linear array and the array of microlenses is a linear array.

11. The apparatus of claim 9 wherein the reflective grating is an echelle grating having a groove spacing of between about 50-300 grooves per millimeter and a blaze angle of between about 51-53 degrees.
12. The apparatus of claim 9 wherein the reflective grating is an echelle grating having a groove spacing of between about 50-300 grooves per millimeter and a blaze angle providing an angular dispersion of between about 0.091 and 0.11 degrees per nanometer for a select order of diffraction of between 4-7.

13. The apparatus of claim 9 wherein the focal point of at least one microlens is in a corresponding waveguide.

14. The apparatus of claim 9 wherein the focal point of at least one microlens is at the propagating end of a corresponding waveguide.

15. The apparatus of claim 9 wherein the reflective grating is spaced a distance from the collimating/focusing lens such that a point on a reflective surface of the grating is spaced the select focal length from the collimating/focusing lens.

16. The apparatus of claim 15 wherein the point on the reflective surface of the grating is at about the center of the reflective surface of the grating.

17. The apparatus of claim 9 wherein the array of micro-lenses is positioned at about a focal plane of the collimating/focusing optic spaced the select focal length from the collimating/focusing optic.