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[54] INTEGRATED BI-DIRECTIONAL AXIAL GRADIENT REFRACTIVE INDEX/DIFFRACTION GRATING WAVELENGTH DIVISION MULTIPLEXER

OTHER PUBLICATIONS

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G. R. Harrison, Ph.D., Sc.D. et al., Practical Spectroscopy, Chapter 4—Diffraction—Grating Spectrographs, Prentice-Hall (1984) (no month available).

W. J. Tomlinson, Wavelength multiplexing in multimode optical fibers, Applied Optics, vol. 16, No. 8 (Aug. 1977).

W. J. Tomlinson et al., Optical multiplexer for multimode fiber transmission systems, Appl. Phys. Lett., vol. 31, No. 3 (Aug. 1977).

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W. J. Tomlinson et al., Optical wavelength-division multiplexer for the 1-1.4 μm spectral region, Electronics Letters, vol. 14, No. 11 (May 25, 1973).

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(List continued on next page.)

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[52] U.S. Cl. .... 385/24; 385/33; 385/34; 385/37; 385/14; 385/49; 385/39; 359/130; 359/131; 372/50

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[58] Field of Search ..... 385/24, 33, 34, 385/37, 14, 49, 39; 359/130, 131; 372/50

[57] ABSTRACT

[56] References Cited

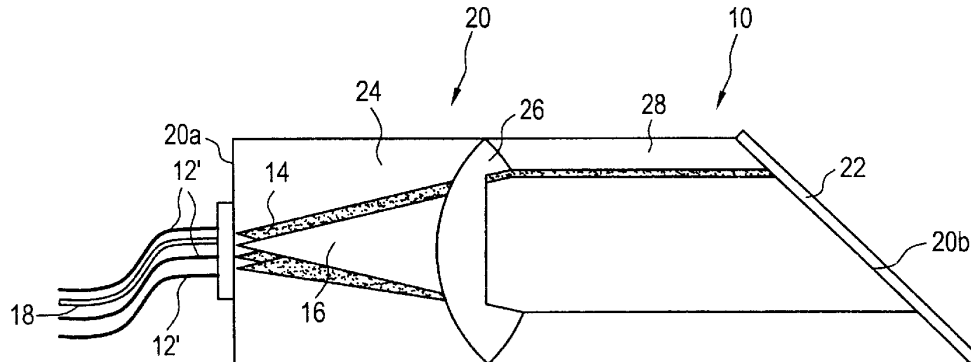
U.S. PATENT DOCUMENTS

4,111,524	9/1978	Tomlinson, III	350/96.19
4,153,330	5/1979	Tomlinson, III	350/96.17
4,198,117	4/1980	Kobayashi	350/96.19
4,274,706	6/1981	Tangonan	350/96.19
4,279,464	7/1981	Colombini	350/96.19
4,299,488	11/1981	Tomlinson, III	356/328
4,343,532	8/1982	Palmer	350/96.19
4,387,955	6/1983	Ludman et al.	350/96.19
4,479,697	10/1984	Kapany et al.	350/96.18
4,522,462	6/1985	Large et al.	350/96.19
4,583,820	4/1986	Flamand et al.	350/96.19
4,622,662	11/1986	Laude et al.	370/3
4,626,069	12/1986	Dammann et al.	350/162.2
4,634,215	1/1987	Reule	350/96.16
4,643,519	2/1987	Bussard et al.	350/96.19
4,652,080	3/1987	Carter et al.	350/96.19
4,671,607	6/1987	Laude	350/96.15
4,703,472	10/1987	Blumentritt et al.	370/3
4,708,425	11/1987	Gouali et al.	350/96.16
4,726,645	2/1988	Yamashita et al.	350/96.18
4,740,951	4/1988	Lizet et al.	370/3

A wavelength division multiplexer is provided that integrates an axial gradient refractive index element with a diffraction grating to provide efficient coupling from a plurality of input optical sources (each delivering a single wavelength to the device) which are multiplexed to a single polychromatic beam for output to a single output optical receiver. The device comprises: (a) means for accepting optical input from at least one optical source, the means including a planar surface; (b) a coupler element comprising (1) an axial gradient refractive index collimating lens having a planar entrance surface onto which the optical input is incident and (2) a homogeneous index boot lens affixed to the axial gradient refractive index collimating lens and having a planar but tilted exit surface; (c) a diffraction grating, such as a Littrow diffraction grating, on the tilted surface of the homogeneous index boot lens which combines a plurality of spatially separated wavelengths from the optical light; and (d) means to output at least one multiplexed, polychromatic output beam, the means including a planar surface. The device may be operated in the forward direction as a multiplexer or in the reverse direction as a demultiplexer.

(List continued on next page.)

32 Claims, 8 Drawing Sheets



## U.S. PATENT DOCUMENTS

4,741,588	5/1988	Nicia et al.	350/96.19
4,744,618	5/1988	Mahlein	350/96.19
4,746,186	5/1988	Nicia	350/96.13
4,748,614	5/1988	Dammann et al.	370/3
4,749,247	6/1988	Large	350/96.16
4,752,108	6/1988	Vollmer	350/96.12
4,760,569	7/1988	Mahlein	350/3
4,763,969	8/1988	Khoe et al.	350/96.19
4,773,063	9/1988	Hunsperger et al.	370/3
4,786,133	11/1988	Gidon et al.	350/96.19
4,819,224	4/1989	Laude	370/3
4,834,485	5/1989	Lee	350/96.19
4,836,634	6/1989	Laude	350/96.19
4,857,726	8/1989	Kinney et al.	250/226
4,923,271	5/1990	Henry et al.	350/96.19
4,926,412	5/1990	Jansson et al.	370/3
4,930,855	6/1990	Clark et al.	350/96.19
4,934,784	6/1990	Kapany et al.	350/96.18
5,026,131	6/1991	Jansson et al.	350/3.7
5,107,359	4/1992	Ohuchida	359/124
5,119,454	6/1992	McMahon	385/49
5,170,451	12/1992	Ohshima	385/43
5,228,103	7/1993	Chen et al.	385/14
5,278,687	1/1994	Jansson et al.	359/125
5,355,237	10/1994	Lang et al.	359/130
5,363,220	11/1994	Kuwayama et al.	359/3
5,371,813	12/1994	Artigue	385/24
5,440,416	8/1995	Cohen et al.	359/127
5,442,472	8/1995	Skrobko	359/110
5,450,510	9/1995	Boord et al.	385/37
5,457,573	10/1995	Iida et al.	359/569
5,500,910	3/1996	Boudreau et al.	385/24
5,513,289	4/1996	Hosokawa et al.	385/33
5,526,155	6/1996	Knox et al.	359/130
5,541,774	7/1996	Blankenbecler	359/653
5,555,334	9/1996	Ohnishi et al.	385/93
5,583,683	12/1996	Scobey	359/127
5,606,434	2/1997	Feldman et al.	359/3
5,657,406	8/1997	Ball	385/24
5,703,722	12/1997	Blankenbecler	359/653
5,742,416	4/1998	Mizrahi	359/134
5,745,270	4/1998	Koch	359/124
5,745,271	4/1998	Ford et al.	359/130
5,745,612	4/1998	Wang et al.	385/24
5,748,350	5/1998	Pan et al.	359/130
5,748,815	5/1998	Hamel et al.	385/37
5,768,450	6/1998	Bhagavatula	385/24
5,777,763	7/1998	Tomlinson, III	359/130
5,835,517	11/1998	Jayaraman et al.	372/50

## OTHER PUBLICATIONS

T. Miki et al., Viabilities of the wavelength-division-multiplexing transmission system over an optical fiber cable, *IEEE Transactions on Communications*, vol. Com-26, No. 7 (Jul. 1978).

K. Aoyama et al., Optical demultiplexer for a wavelength division multiplexing system, *Applied Optics*, vol. 18, No. 8 (Apr. 15, 1979).

K. Aoyama et al., Low-loss optical demultiplexer for WDM systems in the 0.8- $\mu$ m wavelength region, *Applied Optics*, vol. 18, No. 16 (Aug. 15, 1979).

R. Watanabe et al., Optical Demultiplexer Using Concave Grating in 0.7-0.9  $\mu$ m Wavelength Region, *Electronics Letters*, vol. 16, No. 3 (Jan. 31, 1980).

K. Kobayashi et al., Microoptic Grating Multiplexers and Optical Isolators for Fiber-Optic Communications, *Journal of Quantum Electronics*, vol. QE-16, No. 1 (Jan. 1980).

Yohi Fujii et al., Optical Demultiplexer Using a Silicon Echelette Grating, *Journal of Quantum Electronics*, vol. QE-16, No. 2 (Feb. 1980).

W. J. Tomlinson, Applications of GRIN-rod lenses in optical fiber communication systems, *Applied Optics*, vol. 19, No. 7 (Apr. 1, 1980).

A. Nicia, Wavelength Multiplexing and Demultiplexing Systems for Singlemode and Multimode Fibers, *Conference Proceedings, European Conference on Optical Communication* (Sep. 8-11, 1981).

B. D. Metcalf et al., High-capacity wavelength demultiplexer with a large-diameter GRIN rod lens, *Applied Optics*, vol. 21, No. 5 (Mar. 1, 1982).

J. Lipson et al., Low-Loss Wavelength Division Multiplexing (WDM) Devices for Single-Mode Systems, *Journal of Lightwave Technology*, vol. LT-1, No. 2 (Jun. 1983).

G. Winzer, Wavelength Multiplexing Components—A Review of Single-Mode Devices and their Applications, *Journal of Lightwave Technology*, vol. LT-2, No. 4 (Aug. 1984).

H. Ishio et al., Review and Status of Wavelength-Division-Multiplexing Technology and Its Application, *Journal of Lightwave Technology*, vol. LT-2, No. 4 (Aug. 1984).

Y. Fujii et al., Optical Demultiplexer Utilizing an Ebert Mounting Silicon Grating, *Journal of Lightwave Technology*, vol. LT-2, No. 5 (Oct. 1984).

J. Lipson et al., A Four-Channel Lightwave Subsystem Using Wavelength Division Multiplexing, *IEEE Journal of Lightwave Technology*, vol. LT-3, No. 1 (Feb. 1985).

B. Hillerich et al., Wide Passband Grating Multiplexer for Multimode Fibers, *Journal of Lightwave Technology*, vol. LT-3, No. 3 (Jun. 1985).

J. Lipson et al., A Six-Channel Wavelength Multiplexer and Demultiplexer for Single Mode Systems, *Journal of Lightwave Technology*, vol. LT-3, No. 5 (Oct. 1985).

I. Nishi et al., Broad Passband Multi/Demultiplexer for Multimode Fibers Using a Diffraction Grating and Retroreflectors, *Journal of Lightwave Technology*, vol. LT-5, No. 12 (Dec. 1987).

B. Moslehi et al., Fiber-optic wavelength-division multiplexing and demultiplexing using volume holographic gratings, *Optic Letters*, vol. 14, No. 19 (Oct. 1, 1989).

Y. Huang et al., Wavelength-division-multiplexing and demultiplexing using substrate-mode grating pairs, *Optics Letters*, vol. 17, No. 22 (Nov. 15, 1992).

M. Wu et al., Design Considerations for Rowland Circle Gratings Used in Photonic Integrated Devices for WDM Applications, *Journal of Lightwave Technology*, vol. 12, No. 11 (Nov. 1994).

A. Stavdas et al., Design of a holographic concave grating used as a multiplexer/demultiplexer in dense wavelength-routed optical networks with subnanometer channel spacing, *Journal of Modern Optics*, vol. 42, No. 9, pp. 1863-1874 (Sep. 1995).

C. Zhou et al., Four Channel Multimode Wavelength Division Demultiplexer (WDM) System Based on Surface-normal Volume Holographic Gratings and Substrate-guided Waves, *SPIE*, vol. 3288 (no date available).

- A. Stavdas et al., Free-Space Aberration-Corrected Diffraction Grating Demultiplexer for Application in Densely-Spaced, Subnanometer Wavelength Routed Optical Networks, *IEEE Electronic Letters*, vol. 31, No. 16, pp. 1368-1370 (Aug. 1995).
- D. Wisely, High performance 32 channel HDWDM multiplexer with 1nm channel spacing and 0.7nm bandwidth, *SPIE*, vol. 1578, *Fiber Networks for Telephony and CATV* (1991) (no month available).
- A. Cohen et al., Active management of 100-GHz-spaced WDM channels, *Optical Fiber Communication Conference and the International Conference on Integrated Optics and Optical Fiber Communication, Technical Digest, Conference Edition* (Feb. 24, 1999).
- B. Keyworth et al., Low Loss, Temperature Stable Diffraction Grating Wavelength (DE) Multiplexer, *National Fiber Optic Engineers Conference, Technical Proceedings*, vol. 1 (Sep. 13-17, 1998).
- M. Seki et al., 20-Channel Micro-Optic Grating Demultiplexer for 1.1-1.6um Band Using a Small Focusing Parameter Graded-Index Rod Lens, *Electronic Letters*, vol. 18, No. 6 (Mar. 18, 1982).
- A. Koonen, A Compact Wavelength Demultiplexer Using Both Interference Filters and a Diffraction Grating, *European Conference of Optical Communications, Conference Proceedings* (Sep. 8-11, 1981).
- J. Conradi et al., Laser Based WDM Multichannel Video Transmission System, *Electronic Letters*, vol. 17, No. 2 (Jan. 22, 1981).
- J. Laude et al., Wavelength division multiplexing/demultiplexing (WDM) using diffraction gratings, *SPIE*, vol. 503, *Application, Theory, and Fabrication of Periodic Structures* (1984) (No month available).
- A. Livanos et al., Chirped-grating demultiplexer in dielectric waveguides, *Applied Physics Letters*, vol. 30, No. 10 (May 1977).
- H. Obara et al., Star Coupler Based WDM Switch Employing Tunable Devices With Reduced Tunability Range, *Electronic Letters*, vol. 28, No. 13 (Jun. 1992).
- A. Willner et al., 2-D WDM Optical Interconnections Using Multiple-Wavelength VCSEL's for Simultaneous and Reconfigurable Communication Among Many Planes, *IEEE Photonics Technology Letters*, vol. 5, No. 7 (Jul. 1993).
- M. Wang et al., Five Channel Polymer Waveguide Wavelength Division Demultiplexer for the New Infrared, *IEEE Photonics Technology Letters*, vol. 3, No. 1 (Jan. 1991).
- M. Li et al., Two-channel surface-normal wavelength demultiplexer using substrate guided waves in conjunction with multiplexed waveguide holograms, *Appl. Phys. Lett.*, vol. 66, No. 3 (Jan. 1995).
- J. Laude et al., Stimax, A Grating Multiplexer for Monomode or Multimode Fibers, *Ninth European Conference on Optical Communication-ECOC83*, Geneva, Switzerland (Oct. 23-26, 1983).
- W.J. Tomlinson, "Wavelength multiplexing in multimode optical fibers", *Applied Optics*, vol. 16, No. 8, pp. 2180-2194 (Aug. 1977).
- A.C. Livanos et al., "Chirped-grating demultiplexers in dielectric waveguides", *Applied Physics Letters*, vol. 30, No. 10, pp. 519-521 (May 15, 1977).
- Hideki Ishio et al., "Review and status of wavelength-division multiplexing technology and its application", *Journal of Lightwave Technology*, vol. LT-2, No. 4, pp. 448-463 (Aug. 1984).
- H. Obara et al., "Star coupler based WDM switch employing tunable devices with reduced tunability range", *Electronic Letters*, vol. 28, No. 13, pp. 268-270 (Jun. 18, 1992).
- A.E. Willner et al., "2-D WDM optical interconnections using multiple-wavelength VCSEL's for simultaneous and reconfigurable communication among many planes", *IEEE Photonics Technology Letters*, vol. 5, No. 7, pp. 838-841 (Jul. 1993).
- Yang-Tang Huang et al., "Wavelength-division-multiplexing and -demultiplexing by using a substrate-mode grating pair", *Optics Letters*, vol. 17, No. 22, pp. 1629-1631 (Nov. 15, 1992).
- M.R. Wang et al., "Five-channel polymer waveguide division demultiplexer for the near infrared", *IEEE Photonics Technology Letters*, vol. 3, No. 1, pp. 36-38 (Jan. 1991).
- Maggie M. Li et al., "Two-channel surface-normal wavelength division demultiplexer using substrate guided waves in conjunction with multiplexed waveguide holograms", *Appl. Phys. Lett.* vol. 66, No. 3, pp. 262-264 (Jan. 16, 1995).

FIG.1A

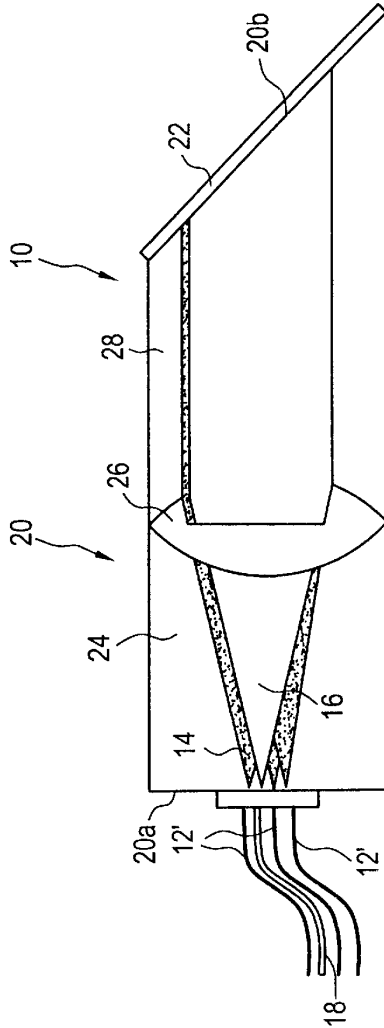


FIG.1B

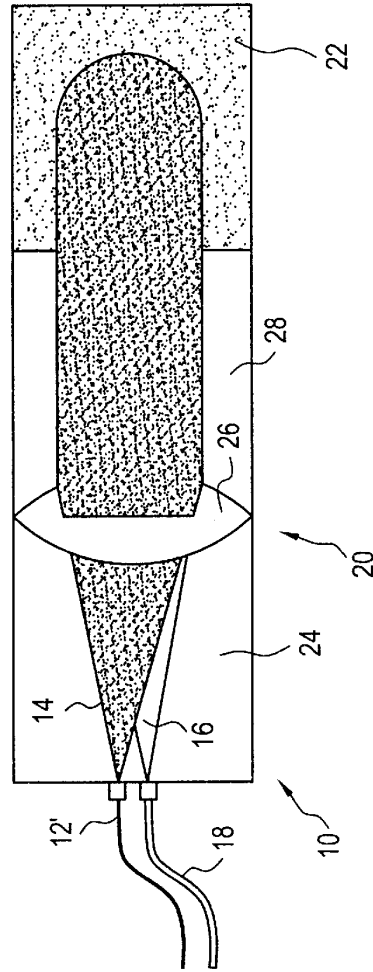


FIG.2B

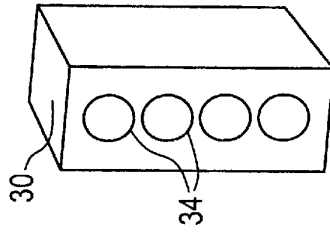


FIG.2C

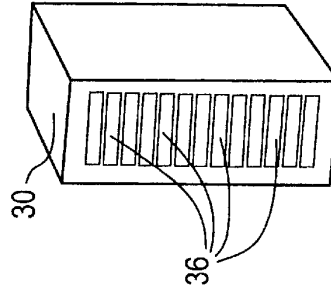
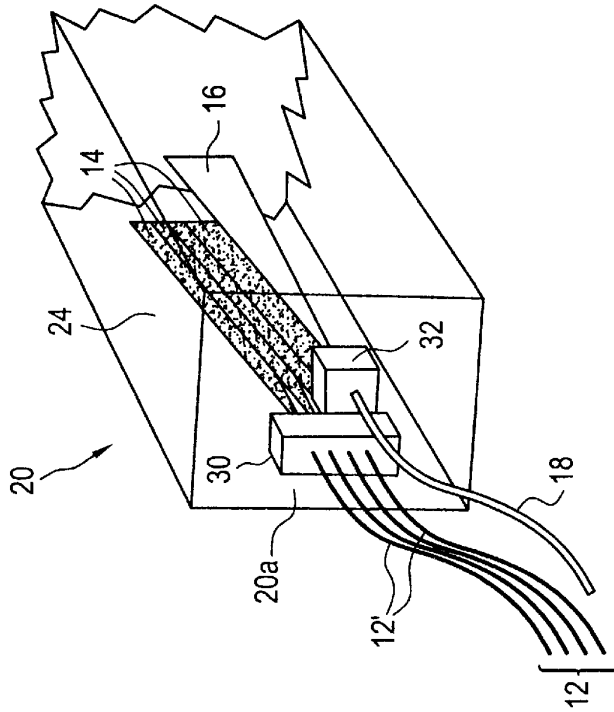


FIG.2A



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