



US006011884A

United States Patent [19]
Dueck et al.

[11] **Patent Number:** **6,011,884**
[45] **Date of Patent:** **Jan. 4, 2000**

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

[75] Inventors: **Robert H. Dueck**, Santa Ana, Calif.; **Robert K. Wade**, Edgewood, N.Mex.; **Boyd V. Hunter**; **Joseph R. Dempewolf**, both of Albuquerque, N.Mex.

[73] Assignee: **LightChip, Inc.**, Salem, N.H.

[21] Appl. No.: **08/990,197**

[22] Filed: **Dec. 13, 1997**

[51] **Int. Cl.**⁷ **G02B 6/28**

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

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

[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

(List continued on next page.)

OTHER PUBLICATIONS

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).

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).

(List continued on next page.)

Primary Examiner—Rodney Bovernick

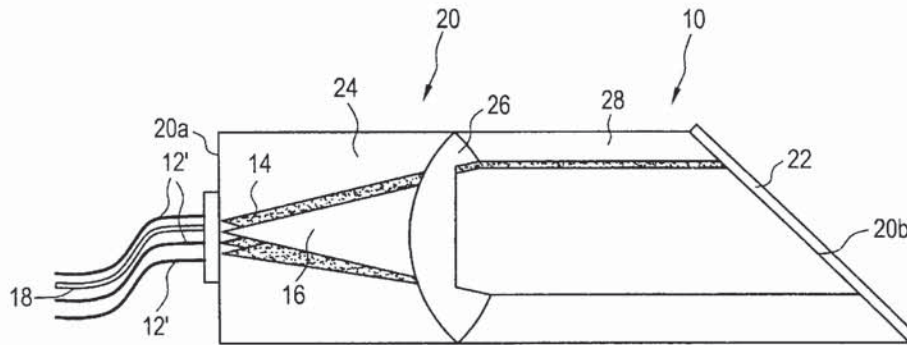
Assistant Examiner—Sung T. Kim

Attorney, Agent, or Firm—Jenkins & Gilchrist, P.C.

[57] **ABSTRACT**

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.

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- μ 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 μ m Wavelength Region, *Electronics Letters*, vol. 16, No. 3 (Jan. 31, 1980).

K. Kobayashi et al., Microopite 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. I (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

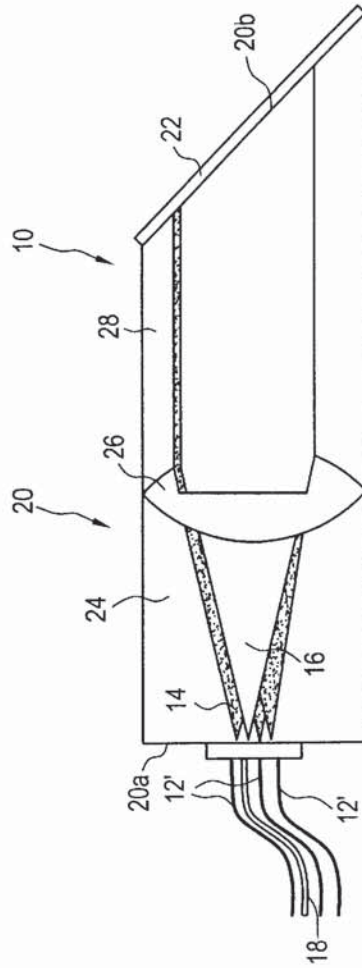


FIG.1B

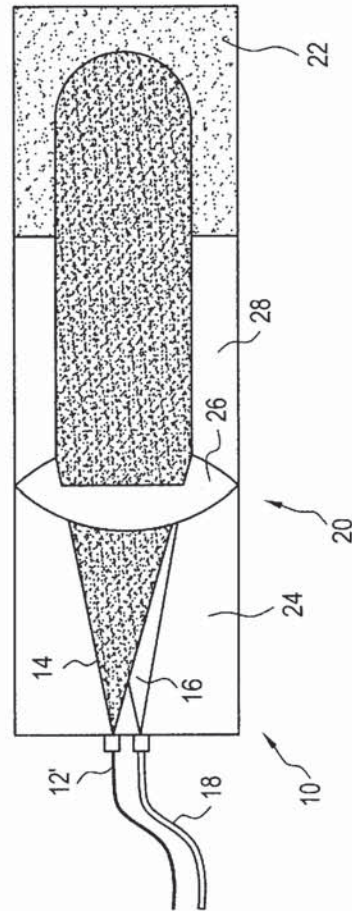


FIG.2B

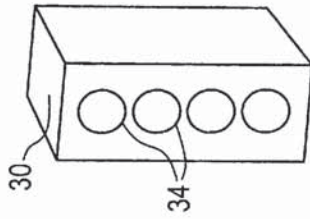


FIG.2C

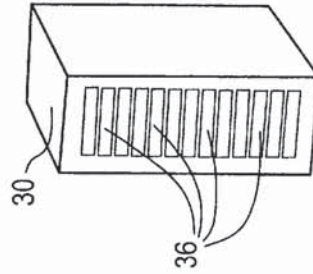
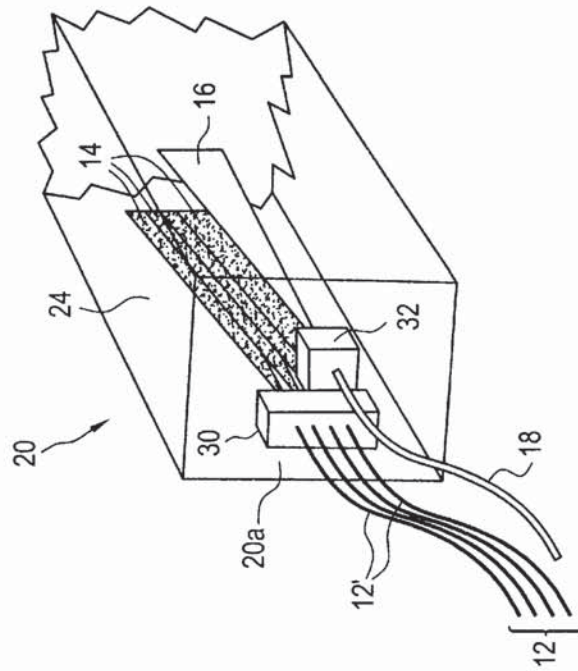


FIG.2A



Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts



Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research



With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips



Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.