Axial-Graded-Index (AGRIN) Lens-Based Eight-Channel Wavelength Division Demultiplexer for Multimode Fiber-Optic Systems

Charles C. Zhou, Ray T. Chen, Boyd V. Hunter, and Paul Dempewolf

Abstract— **We have designed and fabricated the first multimode wavelength division multiplexer (WDM) and demultiplexer (WDDM) based on axial graded index (AGRIN) lenses in conjunction with a volume holographic grating. The demonstration is made using a multimode fiber with a 50-μm core size. The diffraction-limited AGRIN lenses employed significantly increase the output coupling efficiency and reduce crosstalk when compared with the best homogeneous lens solutions previously reported. The volume holographic grating has a maximum diffraction efficiency of 92% at the center wavelength of 780 nm. An eight-channel WDDM device with a center wavelength of 780 nm and a channel separation of 4 nm is designed and demonstrated. The end-to-end insertion loss for each channel is between 2.8 and 3.8 dB. The maximum channel-to-channel crosstalk is -25 dB.**

Index Terms— **Integrated optics, lenses, optical communications, optical fibers, wavelength-division multiplexing (WDM).**

I. Introduction

WAVELENGTH division multiplexing and demultiplexing (WDDM) are considered key technologies to enhance the fiber optic transmission bandwidths. Optical communication systems based on WDDM technologies not only provide high speed data paths, they also provide the convenience of channel independence and data format transparency [1], [2]. In recent years, many practical WDDM device technologies have been developed based on directional couplers, dielectric thin-film optical filters, dispersive gratings, arrayed waveguide gratings, etc. [3]–[6]. WDDM devices are used in single-mode fiber based long distance telecommunications, often in combination with erbium-doped fiber amplifiers (EDFA's) to compensate the insertion loss resulted from the WDDM devices and long transmission distance. For short-haul data communications, multimode fiber is used since the packaging requirements are less stringent while the distance/bandwidth product is acceptable. Many single-mode fiber (SMF)-based WDDM technologies cannot be easily used in a multimode fiber system. For example, arrayed waveguide grating based WDDM provides an excellent channel count and multiplexing/demultiplexing capabilities, but its single-mode feature makes it difficult to be compatible with multimode fiber system. Furthermore, the packaging tolerance for a single-mode system is much more stringent than that of a multimode system. In evaluation of the potential WDDM technologies for multimode optical communication systems, dispersive-grating-based WDDM deems to be most favorable since it provides simultaneous advantages of a large channel count with compact packaging, a low insertion loss and a low crosstalk. Previously, multimode WDDM devices based on homogeneous and radial graded index (GRIN) lenses have been reported [7], [8]. Diffraction-limited optical system performance is lacking in these designs, therefore, limiting their applications. In this letter, we present an eight-channel WDDM device with excellent optical performance using axial graded index (AGRIN) lenses in combination with a high-diffraction efficiency polymer holographic grating.

The WDDM device is shown in Fig. 1. The optical signals from the multimode input fiber (50-μm core size) carrying eight wavelengths are first collimated with an axial graded index (AGRIN) lens. The collimated light is then dispersed by a high-diffraction efficiency dispersive volume holographic grating. The dispersed light beams are bounced back into another focusing AGRIN lens. The wavelength-encoded optical signals with different bouncing angles are focused to form an array of diffraction-limited spots on the output focal plane. A corresponding multimode fiber array is used as output couplers for collecting different wavelengths. Since the fibers and the AGRIN lenses are face-joined, the device is robust and reliable. The maintenance of azimuthal symmetry of the modes guarantees a high-coupling efficiency. The hologram used has a high-diffraction efficiency of 92%, the light dispersion is independent of light polarization. The beam reversal of the same device makes it a WDM.

To achieve the system goals of the WDDM module design, the lens system has to meet a set of operational criteria. The major requirement calls for a planar, inexpensive, high-performance, and miniaturized packaging. Planar surfaces of WDDM devices permit an incoming optical fiber and an output fiber array to be coupled to a flat surface without an air gap. In meeting these requirements, the AGRIN glass material offers a refractive index variation in one dimension, unlike the radial gradient index materials that have been available for years (see Fig. 2). For an axial gradient material, the refractive index varies along the optical axis, as shown in the illustration. Axial gradients plus spherical surfaces

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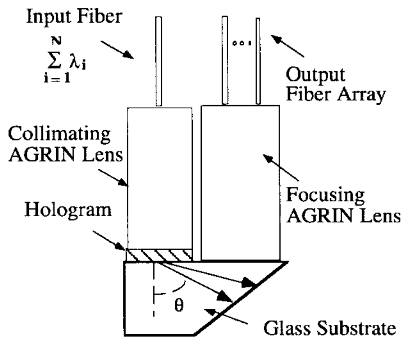


Fig. 1. WDDM based on a dispersive hologram and AGRIN lenses.

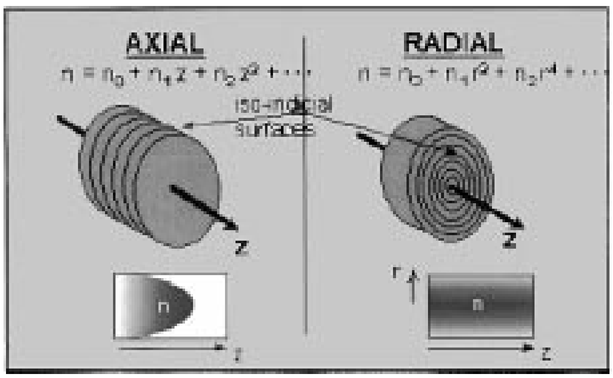
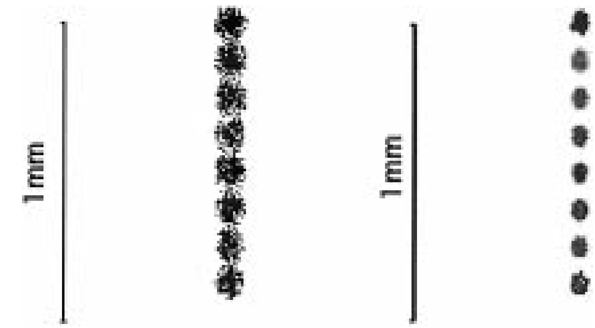


Fig. 2. A comparison of axial and radial gradients. For an axial gradient, the refractive index varies along optical axis, as shown in the illustration on the left. Axial gradients plus spherical surfaces provide excellent aberration correction. A plano–plano axial gradient lens is made by glass blank fusion. In a radial gradient, the refractive index varies perpendicular to the optical axis. The inherent focusing power in radial gradient enables plano–plano radial gradient rod lenses.

provide excellent aberration correction[1] [9]. Flat surfaces can be obtained by inserting glass blanks. In a radial gradient, the refractive index varies perpendicularly to the optical axis. The inherent focusing power in the gradient is the reason this form has been used in plano–plano rod lenses for many years. The important differences between axial graded index glasses and previous gradient materials are the result of manufacturing process stability and profile customization, the ability to design any desired profile shape becomes feasible. Profile repeatability is as good as or better than the normal batch-to-batch variations in optical glasses. Because so many base glasses are available to the AGRIN glass process, a variety of refractive index profiles, dispersion profiles, and mechanical and thermal properties can be engineered, as needed, into the material. These additional degrees of freedom allow the extraction of high performance from the optical system. If the gradient is correctly designed, diffraction-limited performance is achieved meeting all of the design criteria surpassing any optical element using homogeneous optical materials or ion exchange radial gradient materials.

Selection of AGRIN lenses and holographic gratings are based on the WDDM device specifications. With a known center wavelength λ and channel separation $\Delta\lambda$, the output

[1] Lightpath Technologies Inc., product catalog.



(a) (b)

Fig. 3. (a) Spot diagram of a 50-μm input fiber by best homogeneous lens solution. (b) Spot diagram of a 50-μm input fiber by axial graded index lens solution.

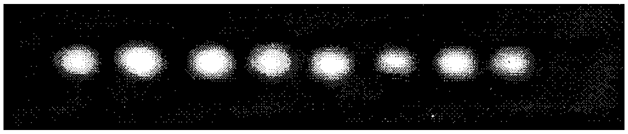
focal length f of the output AGRIN lens is determined by the output fiber spacing D which is expressed as

$$f = D \cdot \frac{\lambda}{\Delta\lambda}\, c\, \tan(\theta). \qquad (1)$$

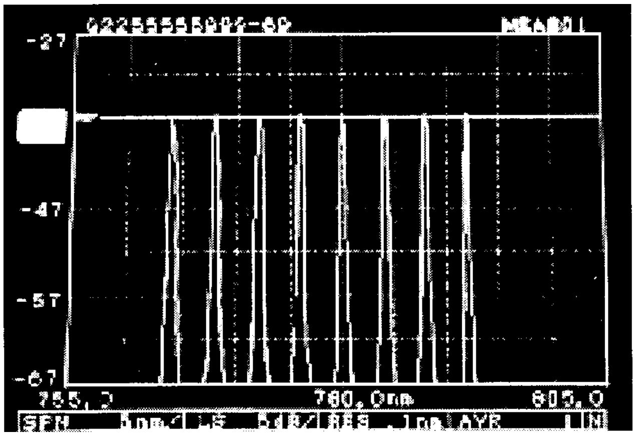
In (1), λ is the center wavelength, $\Delta\lambda$ is the channel separation, and θ is the volume holographic grating diffraction angle. The diffraction angle is usually selected to be larger than the total internal reflection (TIR) angle. The lens aperture should be larger than the input fiber numerical aperture (NA) so that a high-launching efficiency is obtained. For a lens pair having a $1:1$ magnification ratio, the output fiber core diameter d should be much larger than the output lens Airy disk in order to obtain a high coupling efficiency and a lower crosstalk. Once the component parameters are selected, ray tracing and Fourier optical analyses are applied to verify and optimize the system performances such as the output spot separation, the coupling efficiency and the corresponding crosstalk.

For a multimode fiber-based eight-channel WDDM device, we choose two identical lens couplers and a dispersive holographic grating with a 45° diffraction angle. The required center wavelength is 780 nm with a 4-nm channel separation. The input and output multimode fiber chosen is 50/125 multimode fiber with a NA of 0.16. As a result, the lens' focal length is 24.5 mm with a clear aperture diameter of 7.8 mm. To show the excellent diffraction-limited optical performance by AGRIN lens-based WDDM, we compare the performance of the best homogeneous lens solution with our AGRIN lens solution using ray tracing. Fig. 3(a) shows the output spot diagrams of the best homogeneous case. It shows that a homogenous lens solution has a coupling efficiency of 40%. However, the nondiffraction-limited optical performance of a homogeneous lens solution causes severe channel crosstalk which is not acceptable in practical applications. By providing the diffraction-limited AGRIN lens solution shown in Fig. 3(b), the output spot size is only 61 μm with channel crosstalk between 20–40 dB. The coupling efficiency is 68%. It is shown clearly that AGRIN lenses provide better performance in coupling efficiency and crosstalk.

We demonstrate the designed eight-channel WDDM using an AGRIN lens GPX-10-30 (10-mm diameter and 30-mm focal length) and a photopolymer based volume hologram. A Ti : sapphire laser is used to provide a tunable laser source



(a)



(b)

Fig. 4. (a) The output spots of an eight-channel WDDM by using AGRIN lenses. (b) Output optical spectrum of the eight-channel WDDM device.

between 764 and 792 nm. The input fiber is a 50-μm core silica fiber with 0.16 NA. The 45° diffraction angle hologram is fabricated using a 20-μm-thick DuPont photopolymer using a two beam interference method [10]. The maximum diffraction efficiency is 92%. As shown in Fig. 1, the first AGRIN lens collimates light from the input multimode fiber. The collimated light is diffracted at a 45° angle by the holographic grating and bounced into the second AGRIN lens by a wedged substrate. The different wavelength-encoded signals with different bouncing angles are focused onto different spots on the output lens focal plane. The output light spots are magnified by a microscope and recorded by a CCD camera. We find that, due to the excellent optical performance of AGRIN lenses, spot size and crosstalk are significantly smaller compared with the best homogeneous solutions [11]. The output eight-channel output spots and optical spectrum is shown in Fig. 4(a) and (b), respectively. The average output spot size is 66 μm with a channel-to-channel crosstalk less than −25 dB. The average output coupling efficiency is 57%. The end-to-end insertion loss is between 2.8 and 3.8 dB for the eight channels. The modal noise level is determined to be around −50 dB using the method presented in [12].

II. Conclusion

We demonstrate the first multimode WDDM device based on AGRIN lenses and photopolymer based holographic gratings. The diffraction-limited performance significantly improves the coupling efficiency and reduces the channel crosstalk compared with that of the best homogeneous design. An eight-channel WDDM with the center wavelength of 780 nm and channel separation of 4 nm is demonstrated. The insertion loss is between 2.8 and 3.8 dB. The channel crosstalk is less than −25 dB. The simple and reliable AGRIN lens fabrication techniques and the ease of holographic grating fabrication process make it possible for multimode based WDDM's to be used in a wide range of practical applications such as parallel computer links, local-area networks, and simultaneous video and audio transmissions.

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