Multi-Mode Arrayed Waveguide Grating Demultiplexer with Single-Mode Performance and Few-Mode-Fiber Interfaces

Haoshuo Chen(1), Nicolas K. Fontaine(1), Binbin Guan(2), Burcu Ercan(2), Yumeng Zhang(2), Roland Ryf(1), Mark Cappuzzo(3), Bob Keller(3), Yongkang Gao(3), Carlo Ferrari(3), Ryan P. Scott(2), and S. J. Ben Yoo(2)

(1) Bell Laboratories, Alcatel-Lucent, 791 Holmdel Rd., Holmdel, NJ 07733, USA
haoshuo.chen@alcatel-lucent.com
(2) Department of Electrical and Computer Engineering, University of California, Davis, CA 95616, USA
(3) Bell Laboratories, Alcatel-Lucent, 600 Mountain Ave, Murray Hill, NJ 07974, USA

Abstract
We demonstrate an arrayed waveguide grating (AWG) demultiplexer for 3-mode few-mode fiber that obtains single-mode performance using spatial-diversity techniques and hybrid-integration. It comprises a silica AWG, and 3D-waveguide mode multiplexers and a remapping network.

Introduction
Wavelength division multiplexing (WDM) has enabled optical networks to increase the fiber capacity 100x over single-wavelength links. Arrayed waveguide grating (AWG) multiplexers, are key components for combining and separating wavelength channels in WDM routing applications. AWGs for single-mode fiber (SMF) have single-mode input waveguides (IW) and output waveguides (OW) before and after free propagation regions (FPR) 2. Recently, transmission systems have almost exhausted all wavelengths in the C and L-band in a single fiber and the capacity is close to the non-linear Shannon limit 3. To further scale capacity, we must use additional spatial-paths in either multi-mode fiber (MMF) or few-mode fiber (FMF). Both MMF and FMF have been demonstrated successfully for supporting space-division multiplexing (SDM), which enables parallel transmission of many modes 4,5. Directly adapting SMF-based WDM components to MMF and FMF can cause large mode-dependent effects such as mode-dependent loss and mode dependent passband shapes and shifts. To reduce the mode-dependencies, several free space devices have employed spatial diversity techniques by separating the N modes into N Gaussian beams such that each mode effectively sees an identical device. However, these devices are based on bulk free space optics such as diffraction gratings 6,7 and have a large footprint.

In this paper, we demonstrate a compact hybrid-integrated AWG demultiplexer with 5 wavelength channels and 100 GHz spacing that interfaces with FMF that obtains near single-mode performance. It comprises a silica 100G AWG with 16 IWs and 16 OWs, a 3D-waveguide (3DW) mode coupling device with 6 photonic lanterns and remapping waveguides, and a 3-mode FMF fiber array.

Fig. 1: Schematic of an MM-AWG (a) without and (b) with using mode DEMUX/MUX; transfer function and mode mixing between different modes (c) without and (d) with modal dispersion in AWG.

Multi-mode (MM) AWG demultiplexer
As the single-mode IWs and OWs of the AWG become multi-mode, the performance of the AWG will degrade due to differences in the modal dispersions and mode-profiles 8. Figure 1(a) shows the schematic of an AWG with multi-mode IWs and OWs. Different modal profiles in the IW and OW illuminate the arrayed
waveguides with different amplitudes and phases producing mode mixing and passband with unique shapes, which limit the effective passband. Figure 1(c) shows the transfer functions and mode mixing between LP$_{01}$ and LP$_{11}$ modes. In order to directly interface with the conventional MMFs or FMFs which are with a 2D circular core, the FPRs and arrayed waveguides of the AWG need to be multi-mode at least in vertical direction which induces modal dispersion effects. Modal dispersion shifts the focal points for different modes and broadens/blurs the passbands as illustrated in Fig. 1(d).

Figure 1(b) shows a spatial-diversity scheme used to interface MMFs to the AWG demultiplexer (DEMUX) and maintain single-mode performance. A mode DEMUX converts N multiple modes into N spatially separated single modes. Each demultiplexed mode is coupled to a different IW of the AWG DEMUX. After the AWG, a second mode multiplexing device is applied to rebuild the spatial modes and couple them back into a MMF at a selected wavelength. Figure 1(b) gives an example for an MM-AWG supporting 3 spatial modes: LP$_{01}$ and LP$_{11ab}$ is able to demultiplex four wavelengths. Instead of using three separate identical AWGs, a single AWG can be employed by using its mirror-image property.

**Hybrid 3DW/Silica MM-AWG**

Figure 2(a) and (b) show the schematic and image of the hybrid-integrated MM-AWG, respectively. The 100G AWG with 16 IWs and OWs is fabricated on a silica-on-silicon platform. Figure 3 shows the measured transmission spectrum of the silica AWG for IW1 to all OWs. The free spectral range (FSR) of the AWG is 22.4nm. There is a mirror-image relation between the IW and OW of the AWG, shifting the input by M waveguides shifts the output by M waveguides. This property enables a single AWG to act as 3 identical AWGs. In Fig. 2, IW3, IW8 and IW13 are chosen as three IWs which have identical transmission on OW groups: OW1 to OW5, OW6 to OW10 and OW11 to OW15. Figure 2 shows how the 15 OW are remapped and reassembled as five mode-selective photonic lanterns used for mode (de)multiplexing on a 3DW device. Each color represents a different demultiplexed mode from the same fiber. The photonic lanterns consist of 3 unidentical waveguides with a waveguide-to-waveguide spacing of 5.6µm. The 3DW mode coupling device includes 6 photonic lanterns. The chip is 10mm X 20mm with a waveguide pitch of 127µm at the single-mode side. A 3-mode FMF array is assembled in a standard 127µm V-groove with a pitch of 3 X 127µm for the upper 5 fibers supporting 5 different demultiplexed wavelengths.

**Mode dependent loss (MDL) characterization**

Figure 3: Measured transmission spectrum of the silica AWG for IW1 to all OWs.

(a) Swept-laser Interferometer

(b) 32-CH SMF Array

(c) 16 X 16 Silica AWG

**Fig. 4:** Test setup using a swept-laser interferometer for characterizing (a) the single silica AWG and (b) MM-AWG.
Minimizing mode dependent loss (MDL) is important for SDM components because MDL causes capacity loss. An ideal SDM device has unitary transmission (i.e., 0dB MDL) over the whole spectrum. Mathematically, the MDL is the ratio of the maximum and minimum singular value of the device’s transfer matrix. We measure the devices transfer matrix across wavelength using a swept-laser interferometer with spatial-diversity 11. First, we characterize the AWG DEMUX without the 3DW mode MUX/DEMUX and remapping network and Fig. 4(a) shows the setup for characterizing the 3 IWs and 3 OWs of the silica AWG belong to one wavelength group. Figure 5(a) gives the calculated 6 (3 spatial channels X 2 polarizations) singular values and MDL for the λ2 channel centered at 1543.5nm, illustrated in Fig. 2(a). The singular values almost completely overlap and form a passband similar to the AWG demultiplexer without the spatial-diversity unit. Similar performances are observed for the other four wavelength channels. The spreading of the passband is not caused by modal dispersion effects and is mainly introduced by device fabrication errors which can be fixed with another fabrication iteration of the silica AWG.

Next, we characterize the complete device containing the FMF fiber array, 3DW mode MUX/DEMUX and remapper and the silica AWG and the setup is shown in Fig. 4(b). Figure 5(b) shows the results. The external photonic-lantern mode MUX to couple light into the FMF adds 3dB MDL which was deducted from the MM-AWG results. 5dB additional MDL is induced by the photonic lanterns in the 3DW remapping network. For this complete device, we obtain a passband similar to a single-mode AWG. Future devices can improve the MDL by reducing the MDL in the 3DW lanterns, and the passband shifts between the 3 IW/OW groups of the silica AWG.

Conclusions
We proposed a spatial-diversity scheme that can eliminate modal dispersion effects from a MM-AWG. As a proof-of-principle demonstration, we built a 100G MM-AWG demultiplexer with near single-mode performance and direct few-mode-fiber inputs and outputs using hybrid integration of 3D-glass waveguides and a silica-AWG demultiplexer. The MM-AWG demultiplexer is a key component for future SDM-compatible reconfigurable optical add-drop multiplexers (ROADMs).

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