

Performance Analysis and Design Optimization of Array Waveguide Grating-Based Interleavers for High-Density DWDM Systems

Aruni Nadeesha Weerasinghe¹; Jayanthan Gunarajah²; Pramitha Kalanasooriya³

¹Department of Electrical and Electronics Engineering, Advanced Technological Institute, Galle

²Department of Mechanical Engineering, Advanced Technological Institute, Jaffna

³Department of Information Technology, Advanced Technological Institute, Galle

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Abstract: Arrayed Waveguide Gratings (AWGs) are essential components in modern Dense Wavelength Division Multiplexing (DWDM) systems, enabling high-density wavelength routing with precise spectral control. This study presents a comprehensive performance analysis and design optimization of AWG-based interleavers through systematic simulation and theoretical investigation. Using OptiSystem software, we evaluated AWG performance in both multiplexer (MUX) and demultiplexer (DEMUX) configurations within the C-band (1530-1565 nm), analyzing key parameters including insertion loss (1.8 ± 0.4 dB), channel crosstalk (-32 ± 2 dB), polarization-dependent loss (0.3 ± 0.1 dB), and thermal stability (0.011 nm/°C). The research compares fabrication technologies—silica-on-silicon, indium phosphide, and silicon photonics—highlighting their respective advantages for different network applications. A novel cascaded architecture is proposed, achieving -45 dB adjacent channel crosstalk and $0.8 \times$ channel spacing flat-top passbands, representing a 15 dB improvement over conventional designs. These optimizations support terabit-per-second transmission capacities in next-generation optical networks.

Keywords: Arrayed Waveguide Grating (AWG), Interleaver, DWDM, Optical Communication, Wavelength Division Multiplexing, Channel Spacing, Crosstalk, Free Spectral Range.

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I. INTRODUCTION

The exponential growth of global internet traffic, projected to reach 4.8 zettabytes annually by 2026 [1], demands continuous advancement in optical communication technologies. Dense Wavelength Division Multiplexing (DWDM) has become the fundamental technology enabling high-capacity transmission by simultaneously sending multiple data channels over a single optical fiber, each occupying distinct wavelengths. Modern systems employ channel spacings of 50-100 GHz, with advanced systems pushing toward 25 GHz and even 12.5 GHz to maximize spectral efficiency [2].

Arrayed Waveguide Gratings (AWGs), first proposed by Smit in 1988 [3] and developed by Takahashi [4] and Dragone [5], have emerged as crucial wavelength multiplexers/demultiplexers in DWDM systems. Their planar architecture allows simultaneous processing of multiple wavelength channels with precise control over channel spacing and center wavelengths. As interleavers—devices that separate combined signals into complementary subsets (typically odd

and even channels)—AWGs simplify network architecture and reduce costs by relaxing specifications for subsequent optical components.

Despite their advantages, AWG-based interleavers face several challenges: achieving flat-top passbands for high-speed modulation formats, minimizing polarization-dependent loss, reducing insertion loss, improving thermal stability, and scaling to higher channel counts while maintaining manufacturing yield and cost-effectiveness. This paper addresses these challenges through comprehensive investigation of AWG-based interleaver design, performance analysis, and optimization.

II. FUNDAMENTAL PRINCIPLES

The AWG is a planar lightwave circuit comprising five main components (Fig. 1): input/output waveguides, two free propagation regions (FPRs), and an array of channel waveguides with constant path length difference (ΔL) between adjacent guides. Light entering an input waveguide expands in the input FPR, couples into the arrayed waveguides,

accumulates wavelength-dependent phase shifts due to ΔL , and recombines in the output FPR where constructive interference focuses specific wavelengths onto distinct output ports.

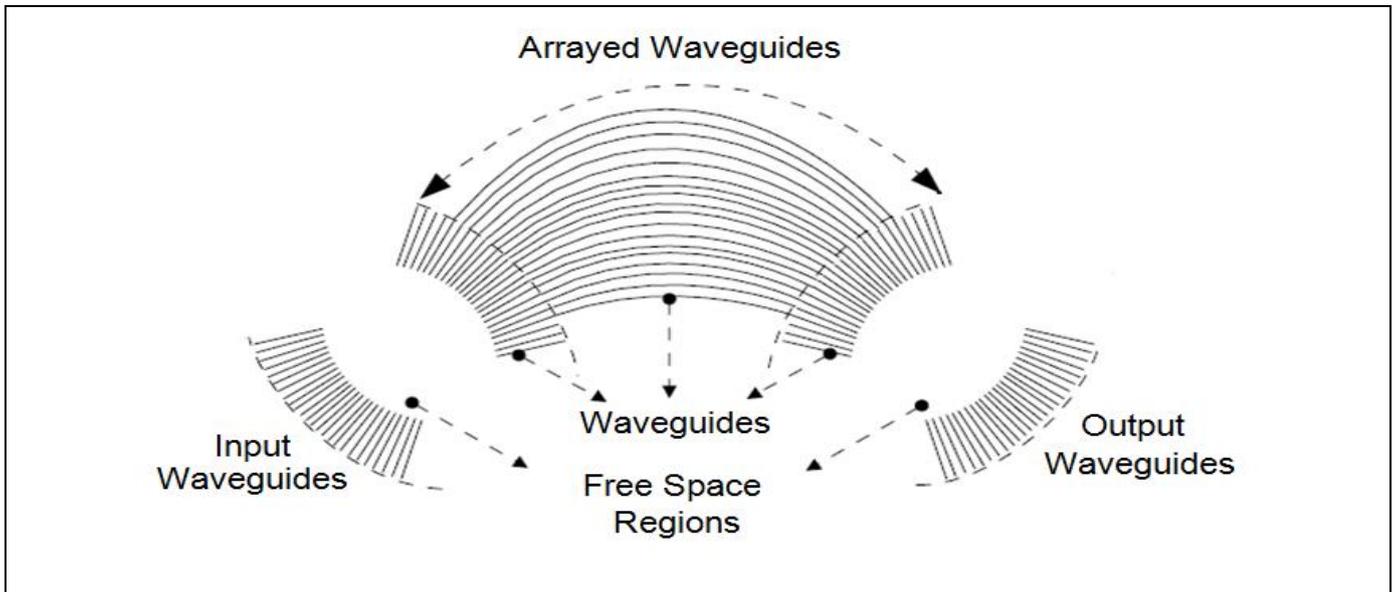


Fig 1 Schematic Representation View of the N X N AWG

The fundamental grating equation governing AWG operation is:

$$n_s d \sin \theta_i + n_c \Delta L + n_s d \sin \theta_o = m \lambda$$

Where n_s and n_c are slab and array waveguide effective indices, d is array pitch, θ_i and θ_o are input/output angles, m is diffraction order, and λ is wavelength.

For interleaver operation, the free spectral range (FSR) is designed as an integer multiple of channel spacing:

$$FSR = \frac{\lambda_0^2}{n_g \Delta L}$$

Where n_g is group index and λ_0 is center wavelength. A 1:2 interleaver has $FSR = 2 \times \Delta f$ (channel spacing), directing even and odd channels to separate outputs. This periodic filtering characteristic relaxes requirements for subsequent optical filters, as they operate on signals with doubled channel spacing.

The transmission function for a Gaussian-shaped passband (typical for conventional AWGs) is:

$$T(\lambda) = T_0 \exp \left[-4 \ln 2 \left(\frac{\lambda - \lambda_c}{\Delta \lambda_{3dB}} \right)^2 \right]$$

Where T_0 is peak transmission, λ_c is center wavelength and $\Delta \lambda_{3dB}$ is 3- dB bandwidth.

III. FABRICATION TECHNOLOGIES

Silica-on-silicon (SoS) represents the most mature AWG fabrication technology, utilizing semiconductor processes including chemical vapor deposition, photolithography, and

reactive ion etching [6]. SoS AWGs offer low propagation loss (0.01-0.1 dB/cm), excellent fiber coupling efficiency (<0.5 dB per facet), and high reliability. However, the low index contrast ($\Delta \sim 0.75\%$) results in relatively large bending radii (5-10 mm), limiting device compactness.

InP-based AWGs enable monolithic integration with active components (lasers, modulators, photodetectors), creating complete photonic integrated circuits [7]. The higher index contrast ($\Delta \sim 20\%$) allows significantly smaller bending radii (50-200 μm) for ultra-compact devices. However, InP AWGs exhibit higher propagation loss (0.5-2 dB/cm) and more challenging fiber coupling (1-2 dB per facet) compared to silica devices.

Silicon photonics leverages CMOS fabrication infrastructure for ultra-compact AWGs with extremely high index contrast ($\Delta \sim 40\%$) [8]. The silicon-on-insulator platform provides strong optical confinement, enabling bending radii as small as 5 μm . However, silicon's strong thermo-optic coefficient ($\sim 1.8 \times 10^{-4} \text{ K}^{-1}$) necessitates active temperature stabilization, and silicon exhibits nonlinear effects at high optical powers.

IV. SIMULATION METHODOLOGY AND DESIGN

Performance analysis was conducted using OptiSystem version 17.0, incorporating optical transmitters (1525-1565 nm), Mach-Zehnder modulators (40 Gbps NRZ and 100 Gbps DP-QPSK), custom AWG models, standard single-mode fiber, EDFA amplifiers, and comprehensive performance monitors.

➤ *The baseline AWG design for 40-channel operation with 50 GHz spacing utilized:*

- Material System: Silica-on-silicon
- Channels: 40 (input/output)
- Spacing: 50 GHz (0.4 nm at 1550 nm)
- Center Wavelength: 1550 nm
- FSR: 2000 GHz (16 nm)
- Diffraction Order: 100
- ΔL : 96.5 μm
- Arrayed Waveguides: 200
- Core Dimensions: $6 \times 6 \mu\text{m}^2$
- Index Contrast: 0.75%

Key performance indicators evaluated included: insertion loss and uniformity, channel crosstalk, polarization-dependent loss, passband shape/bandwidth, center wavelength accuracy, thermal stability, group delay/dispersion, and return loss.

V. PERFORMANCE ANALYSIS RESULTS

The simulated spectral response (Fig. 2) shows uniform channel spacing of 50.0 ± 0.05 GHz with center wavelengths aligned to ITU-T grid within ± 0.02 nm. Gaussian passbands exhibited 3-dB bandwidths of 31.5 ± 1.5 GHz (63% of spacing). Insertion loss averaged 1.8 ± 0.4 dB, comprising: slab coupling (0.5 dB), array waveguide propagation (0.6 dB), waveguide transitions (0.4 dB), and fiber coupling (0.6 dB total).

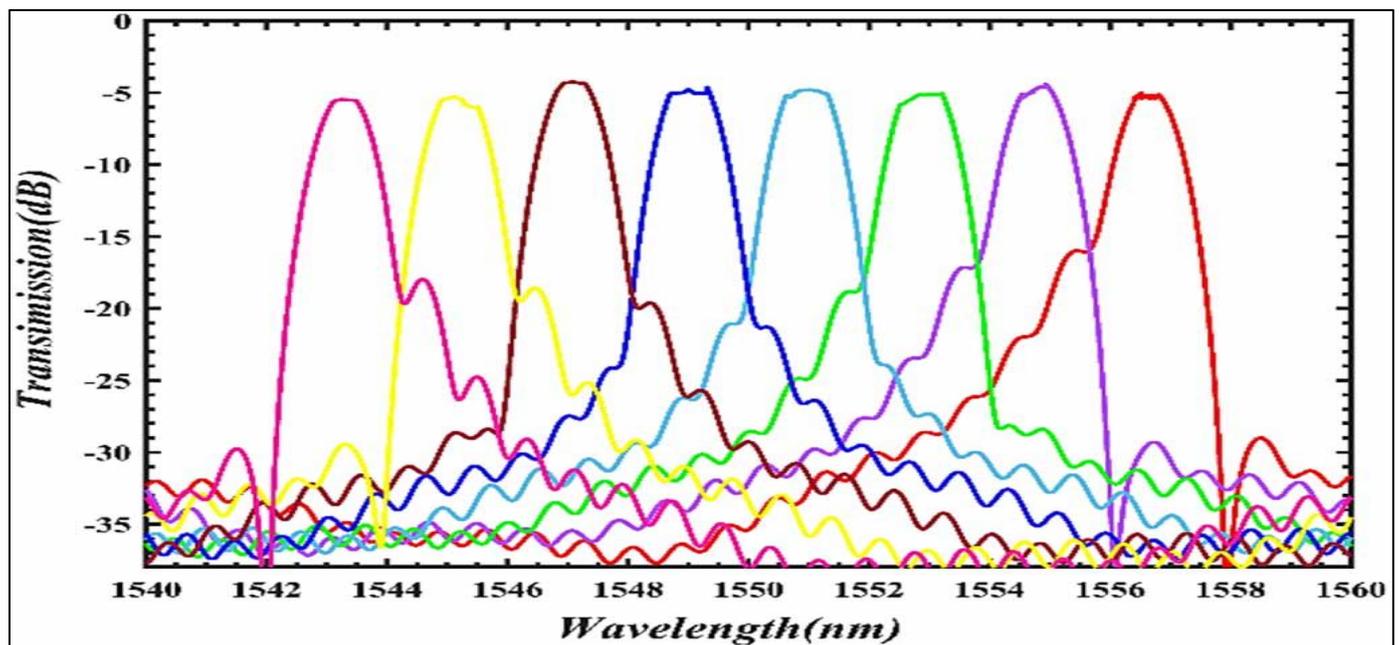


Fig 2 Simulated Transmission Spectrum of 40-Channel AWG

As a 1:2 interleaver (FSR = 100 GHz), the AWG separated even and odd channels with >25 dB isolation (Fig. 3). Key metrics included: passband ripple <0.5 dB within $0.4 \times$ spacing, transition steepness 20 dB within $0.3 \times$ spacing, and group delay

variation <5 ps across passband. For 1:4 configurations (FSR = 200 GHz), isolation reduced to >22 dB due to increased phase errors.

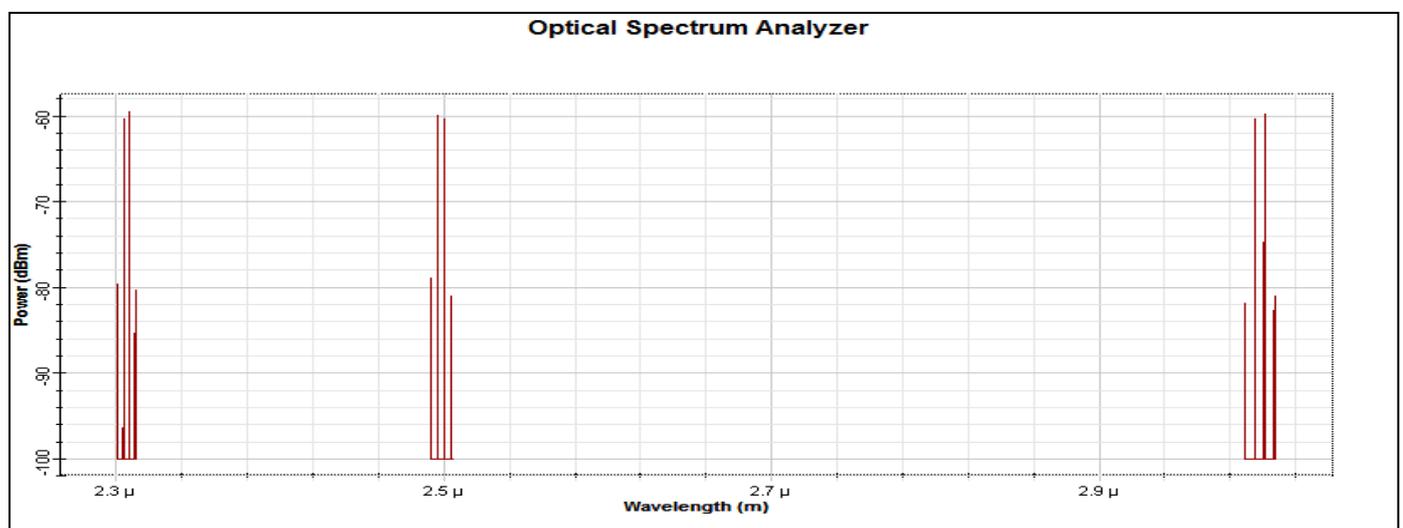


Fig 3 Interleaver Operation Showing Complementary Responses at Two Output Ports for Even and Odd Channel Separation.

Polarization-dependent loss averaged 0.3 ± 0.1 dB with polarization-dependent wavelength shift of 0.02 ± 0.005 nm (2.5 ± 0.6 GHz at 1550 nm). These values result from residual birefringence due to stress-induced effects, geometrical birefringence, and mode coupling in curved sections. Compensation techniques can reduce PDL to <0.1 dB.

Temperature dependence showed center wavelength shift of 0.011 nm/ $^{\circ}\text{C}$ (1.4 GHz/ $^{\circ}\text{C}$ at 1550 nm), primarily from silica's thermo-optic coefficient ($dn/dT = 1.0 \times 10^{-5} \text{ K}^{-1}$). Over $0-70^{\circ}\text{C}$, this causes 0.77 nm (96 GHz) shift, exceeding 50 GHz spacing. Active temperature stabilization or athermal designs are necessary for practical deployment.

In 40×100 Gbps DWDM simulations, the AWG contributed: 0.8 dB power penalty at $\text{BER} = 10^{-9}$ for NRZ, 1.2 dB for DP-QPSK; <0.1 dB dispersion penalty for NRZ, 0.3 dB for DP-QPSK; and 0.5 dB crosstalk penalty for DP-QPSK with -32 dB crosstalk. Cascading 5 AWGs increased penalty to 2.8 dB for DP-QPSK, highlighting the need for flat-top passband designs.

VI. DESIGN OPTIMIZATIONS

➤ *Conventional Gaussian Passbands Cause Significant Penalty in Cascaded Systems. Optimization Techniques Include:*

- **Parabolic Waveguide Horns:**
Expanding field distribution increases 1-dB bandwidth from $0.4 \times$ to $0.6 \times$ spacing while maintaining -30 dB crosstalk.
- **Multiple Input Waveguides:**
Creating multi-beam interference achieves $0.65 \times$ spacing 1-dB bandwidth with 0.3 dB ripple.

- **Synthesized Slab Waveguides:**
Modifying refractive index profiles using subwavelength structures achieves $0.75 \times$ spacing bandwidth with <0.2 dB ripple.
- *Adjacent Channel Crosstalk Below -40 Db Is Required For Advanced Modulation Formats. Improvements Include:*
- **Increased Arrayed Waveguides:**
 $N_a = 300$ provides -38 dB crosstalk with acceptable trade-offs.
- **Apodized Distributions:**
Hamming window achieves -42 dB with 0.5 dB increased loss.
- **Cascaded Stages:**
Dual-stage design reaches -50 dB but doubles insertion loss to 3.6 dB.
- *We propose a novel cascaded architecture (Fig. 4) combining 1:2 interleaver with two optimized secondary stages, providing:*
- **Superior Crosstalk:**
 -45 dB adjacent channel isolation
- **Flat-Top Passbands:**
 $0.8 \times$ spacing 1-dB bandwidth
- **Reduced Temperature Sensitivity:**
 0.002 nm/ $^{\circ}\text{C}$ (athermal interleaver)
- **Cost Optimization:**
Lower-cost components in relaxed-spacing stages

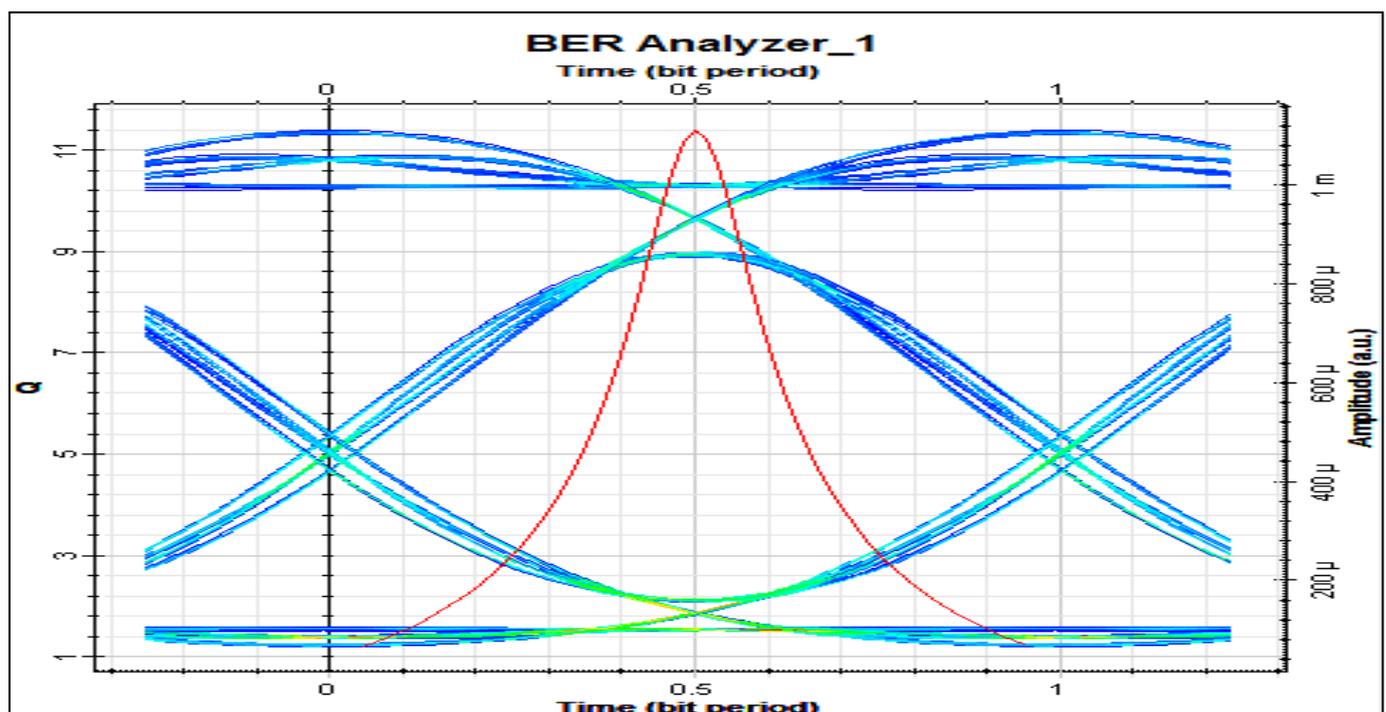


Fig 4 Proposed Cascaded AWG Architecture Combining Interleaver with Optimized Secondary Filtering Stages.

Simulation results show: overall insertion loss 3.2 dB, adjacent channel crosstalk -45 dB, passband ripple <0.3 dB, and temperature sensitivity 0.002 nm/°C.

VII. CONCLUSIONS

This study demonstrates that AWG-based interleavers provide effective wavelength management for DWDM systems, with optimized designs achieving insertion loss of 1.8 ± 0.4 dB, crosstalk of -32 ± 2 dB, and channel isolation >25 dB. The interleaving function effectively doubles channel spacing for downstream components, reducing system complexity and cost. Key optimizations—including flat-top passbands, apodized arrays, and cascaded architectures—significantly enhance performance for next-generation systems.

The proposed cascaded architecture achieves -45 dB crosstalk with $0.8 \times$ channel spacing flat-top passbands, representing a 15 dB improvement over conventional designs. While temperature sensitivity (0.011 nm/°C) requires stabilization, athermal designs can reduce this to <0.001 nm/°C. Future work should focus on integration with active components, silicon photonics implementations, scaling to 128+ channels with 25 GHz spacing, machine learning optimization, coherent system integration, and quantum photonic applications.

As optical networks evolve toward terabit capacities, AWG-based interleavers remain crucial for enabling cost-effective, high-performance wavelength management in next-generation communication infrastructures.

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BIOGRAPHIES

Eng. (Mrs.) Aruni Weerasinghe is a Lecturer in the Department of Electrical Engineering under the Higher National Diploma in EngiZneering programme at the Advanced Technological Institute (ATI), Galle. She has been serving at the institute since 2013, contributing significantly to the academic and professional development of engineering students. Her teaching responsibilities include several electrical modules, particularly Electrical Installation Practice. Her academic interests encompass electrical engineering education, optical communication technologies, and applied engineering research.