

Towards RGB Combiner for AR/VR applications on AlOx

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Aluminum oxide (AlOx) offers low optical loss and high transparency in the visible spectrum, making it a promising material for integrated photonics in display technologies such as augmented/virtual reality (AR/VR) and glassless 3D displays. This paper explores the development of an RGB beam combiner on an aluminum oxide platform, leveraging Mach-Zehnder modulators (MZM) and multimode interference (MMI) structures to manipulate light intensity and achieve precise color control. The combiner design incorporates wavelength-specific gratings to radiate red (635 nm), green (520 nm), and blue (452 nm) light into far field at an exact propagation angle. MZMs control the intensity of each wavelength, allowing dynamic color tuning by modulating the beam interference. This signal can serve as the basis for a pixel building block in display technologies, offering flexible color manipulation at the pixel level.

Introduction

Integrated photonics is rapidly advancing and making new, sophisticated technologies possible. One area that benefits greatly from these advances is 3D display systems, particularly autostereoscopic displays. These displays generate 3D images without the need for special glasses, creating a more immersive experience for the viewer. Achieving such effects requires precise control of light—specifically, the ability to manipulate the intensity and color of light at the pixel level. Integrated photonics enables this control in a compact and scalable format, which is crucial for high-resolution and energy-efficient 3D displays[1].

Among the various materials used in integrated photonics, aluminum oxide stands out as particularly suitable for visible-light applications. It offers low optical loss and excellent transparency across the visible spectrum, making it ideal for devices that require the manipulation of red, green, and blue (RGB) light [2]. These three colors are the foundation of full-color displays, which are used in systems like augmented and virtual reality (AR/VR) and glassless 3D displays [1]. By integrating the control of RGB light into a single platform, more efficient and compact display systems can be created, driving the next generation of visual technologies.

Recent developments have demonstrated various approaches for integrating RGB light on a chip [3],[4], [5]. This paper explores a novel design for an RGB beam combiner on an aluminum oxide platform, which combines light from the red (650 nm), green (532 nm), and blue (450 nm) channels into a single tunable output. The design utilizes Mach-Zehnder modulators (MZMs) to control the intensity of each color channel and multimode interference (MMI) structures to combine the beams into one output. The MZMs allow for dynamic tuning of each color, enabling fine control of the RGB signal serving as a building block for a pixel.

By leveraging aluminum oxide's properties and the efficiency this RGB combiner offers a scalable and compact solution for 3D display technologies. Its design is flexible, allowing for future enhancements such as the incorporation of an array of slanted gratings to achieve autostereoscopic effect [6] by directing the light at different angles without the need of phase tuning of each individual grating. The development of this RGB beam combiner could lead to smaller, more energy-efficient, and higher-performing displays for a wide range of applications, from entertainment to medical imaging, holography and beyond.

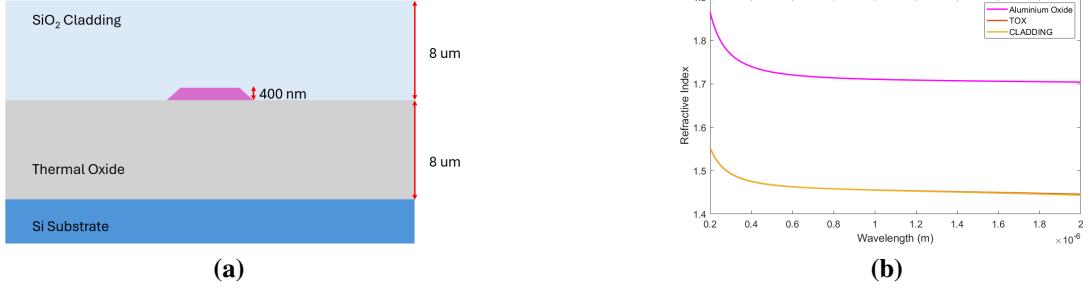


Figure 1: (a) Layerstack of the proposed concept. (b) Refractive index profile of the platform.

Design

Figure 1 presents the layers stack of the platform. Aluminium oxide is 400nm thick and the thicknesses of cladding and Thermal oxide are 8μm.

Figure 1 presents the refractive index profile of the platform. It illustrates that the platform provides a broad transparent window, enabling a range of interesting applications.

Figure 2 illustrates the concept for a single RGB pixel in the proposed beam combiner design. The system begins by inputting red (650 nm), green (532 nm), and blue (450 nm) light into the Mach-Zehnder modulators (MZMs). These modulators control the intensity of each color channel by modulating the phase and amplitude of the light. After modulation, the RGB light channels are combined in multimode interference (MMI) structures, which mix the modulated light and direct it towards the wavelength-specific gratings. These gratings then diffract the combined light into the far field. By adjusting the intensity of each color channel, the system can create a wide range of colors. This process allows for precise and dynamic color control at the pixel level, making it possible to produce various colors by changing the intensities of the red, green, and blue components.

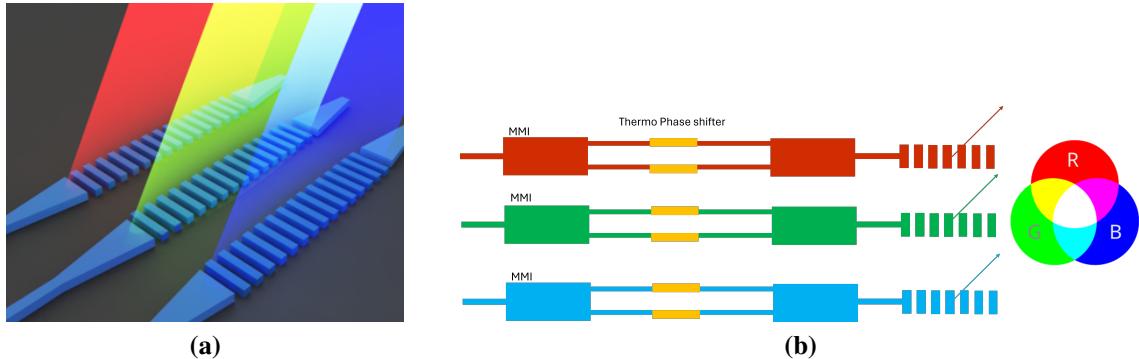


Figure 2: (a)Concept for a single RGB pixel in the proposed beam combiner design. (b) 3D visualization, schematic layout.

The gratings are designed to radiate light at specific angles; in this case, at approximately 25°. The chosen radiation angle corresponds to the smallest achievable grating period supported by the foundry design rules—200nm for the blue grating. Attempts to design with smaller periods were unsuccessful, as the grating teeth merged or collapsed during fabrication. The selected angle ensures well-defined grating features while maintaining the desired optical performance. Alternatively, a thin layer stack can be used to mitigate this issue caused by lithography aspect ratio limitations and resist characteristics.

The periods of the gratings are carefully adjusted to control the angle of light emission: 400 nm for blue light, 460 nm for green light, and 575 nm for red light and the gratings are fully etched 3. Additionally, the gratings are engineered to direct 40-50% of the light in the upward direction. This is accomplished by making the gratings sufficiently long, compensating for the low index contrast of the material fig. 4.

Mach-Zehnder modulators (MMIs) are integral to our design for manipulating beam intensity and color. MMIs utilize interference effects to control the phase and amplitude of light. By adjusting the phase difference between the two arms of the modulator, we can modulate the intensity of the output beam, enabling

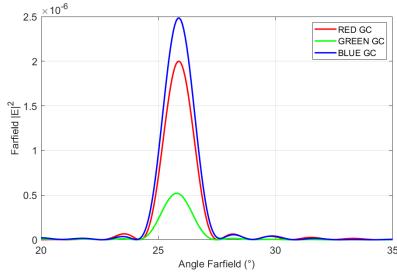


Figure 3: Grating design showing the farfield of RGB Light.

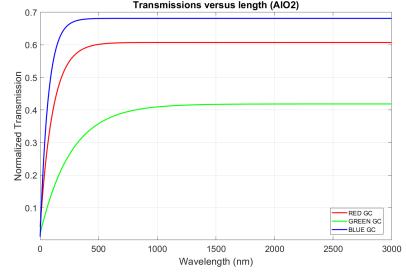


Figure 4: Grating design illustrating the upward light emission versus length of RGB Gratings.

precise control over color mixing and beam combination.

The graph in Figure 5 illustrates the relationship between phase and amplitude changes in the MMI. It shows how varying the phase difference affects the amplitude of the transmitted light, demonstrating the modulator's ability to finely tune the light intensity and color output.

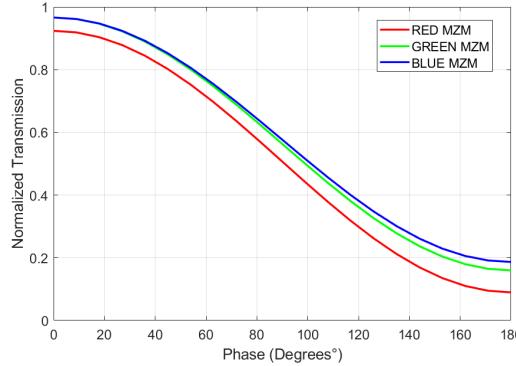


Figure 5: Phase versus amplitude change in the Mach-Zehnder modulator.

Figure 6 demonstrates the effects of constructive and destructive interference in MMIs when the phase of the light is altered in one arm of the interferometer. The MMIs are designed specifically for each target wavelength to ensure optimal performance.

The full mask layout for the system to be fabricated is shown in Figure 14. The input section is designed to match the standard fiber array pitch of 127 μm . The output at the chip edge also emits an RGB signal via edge-fire emission, which can be used for spectral analysis and later compared with the grating-based emission. The overall device footprint is 4 mm \times 1 mm, making it a compact and efficient combiner suitable for augmented reality (AR) and virtual reality (VR) glasses and display systems. In future iterations, the lasers can be integrated on-chip to enable a fully integrated light engine.

For the next iteration, we will replace the Mach-Zehnder modulators (MMIs) with directional couplers (DCs) to reduce losses and reflections. Additionally, modifications to the grating layer stack will be made to improve upward directionality while maintaining compact grating dimensions. Ongoing research is focused on developing RGB on chip combiners on different material platforms which can potentially enable a more compact design and facilitate higher-resolution integration of the gratings.

Experimental

To demonstrate the operation of the gratings in the visible wavelength range on aluminium oxide platform, a high-power Fianium supercontinuum laser was used as the input source. This broadband light enabled the generation of a well-defined visible spectrum (“rainbow”) at the grating outputs. The image below shows a close-up view of light coupling into the photonic chip using the Fianium laser, along with the resulting rainbow patterns emitted from the grating structures.

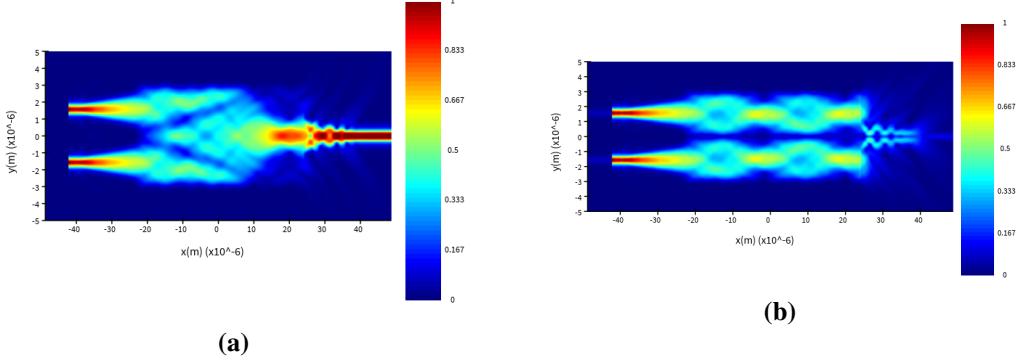


Figure 6: Illustration of the interference behavior in the Mach-Zehnder modulator: (a) constructive interference and (b) destructive interference.

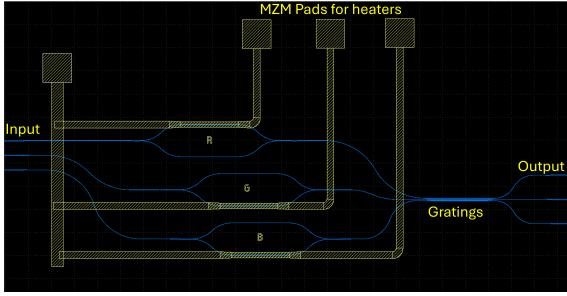


Figure 7: Full mask layout of the system for fabrication.

Light from the green, red, and blue lasers was coupled into the chip via single-mode fibers optimized for each respective wavelength. This allowed for initial propagation testing within the waveguides. The out-coupled light, emitted through surface gratings, was then projected vertically and captured by a CCD camera positioned above the chip.

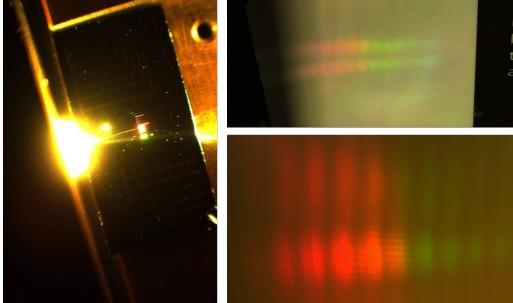


Figure 8: RGB Combiner Under the Microscope

In this setup, RGB laser light is coupled into the photonic chip using a fiber array or alignment stage. As the light propagates through the on-chip waveguides, it is emitted out of plane through surface gratings. A photosensitive card is used to visualize the direction and color of the emitted beams. The images clearly show red, green, and blue emission patterns from different waveguides, confirming successful out-coupling and spatial separation of the RGB channels. This experimental demonstration serves as an important step in validating the grating design and beam alignment for RGB beam combining and projection applications.

This figure shows the RGB combiner imaged under the microscope, where the emission from the surface gratings is captured directly by a camera sensor. Each color—red, green, and blue—is launched into separate input waveguides and then emitted out of plane through the corresponding grating structures. The resulting images show distinct and well-confined beam spots for each wavelength, verifying that the gratings are functioning effectively in the visible range and that the RGB beams are individually addressable.

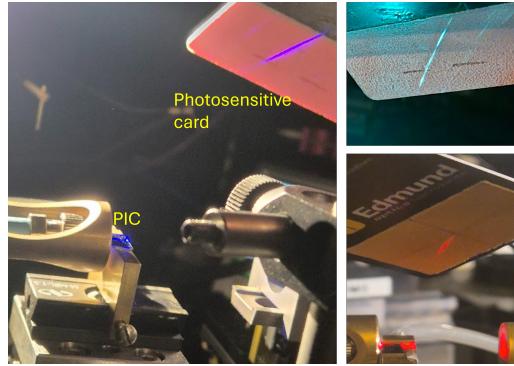


Figure 9: Photonic integrated circuit and grating emission for RGB gratings projected on card

and spatially separated. This setup is crucial for validating the emission directionality and spatial alignment of the combiner design.

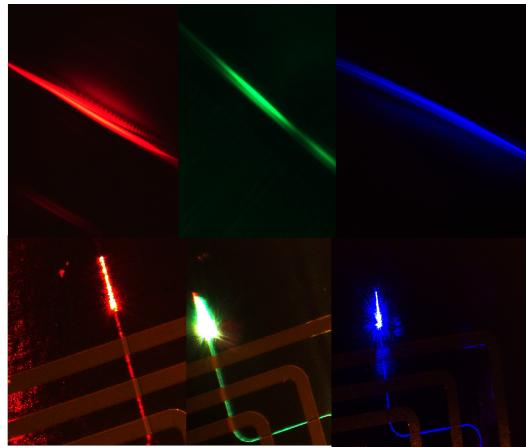


Figure 10: RGB Combiner Under the Microscope for individual Gratings and waveguides

The following pictures shows coupling from the fiber array simultaneously in the waveguide it can be seen at the output that white light is produced from the RGB gratings.

The image below shows the emission colors observed under a microscope for different laser inputs on the photonic chip gratings. A noticeable pink emission appears when blue and red lasers are input, while an orange emission is seen with red and green lasers. The final image demonstrates out-of-plane emission not through the gratings, but via edge waveguides, which also correspond to the output in the chip layout.

The final image shows multiple emissions from the gratings, indicating possible multimode behavior. Since the input fiber array operates at telecom wavelengths and the blue waveguide is only $0.5\mu\text{m}$ wide, care must be taken to avoid excitation of higher-order modes during propagation. The gratings, designed to be $10\mu\text{m}$ wide, were optimized for a smaller diffraction angle; however, the tapered regions may contribute to the observed multimode diffraction patterns. Additionally, the $1\mu\text{m}$ spacing between adjacent gratings and their $500\mu\text{m}$ length may lead to coupling effects. Further investigation is required, including the use of a single-mode fiber array for visible wavelengths to ensure single-mode propagation. Future designs will aim to enforce single-mode behavior across all waveguides. A focusing lens can be employed at this stage to localize the input spot and support further system testing.

A single-mode fiber was used to couple green light into the device. However, it was observed that the green light also coupled into adjacent gratings, gratings were designed 600nm close. resulting in three emission patterns corresponding to the neighboring red and blue gratings. This behavior is demonstrated in the figure below.

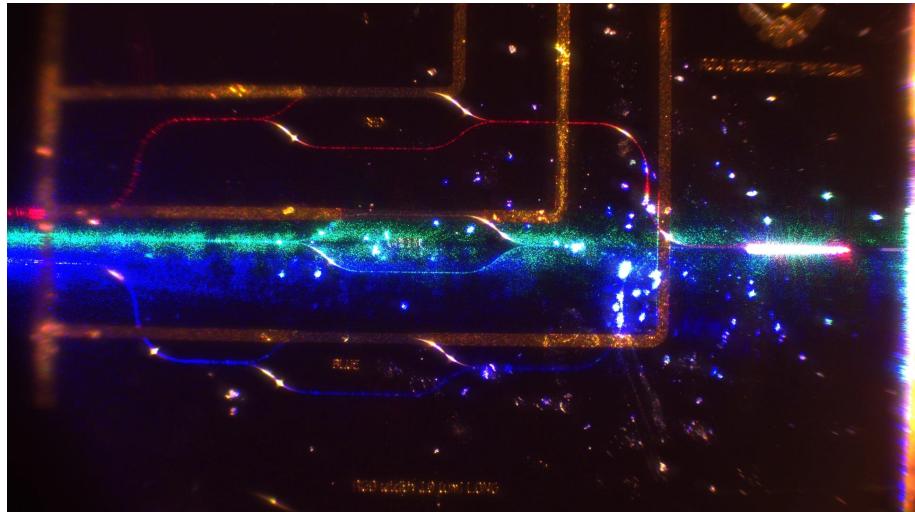


Figure 11: RGB Combiner Under the Microscope

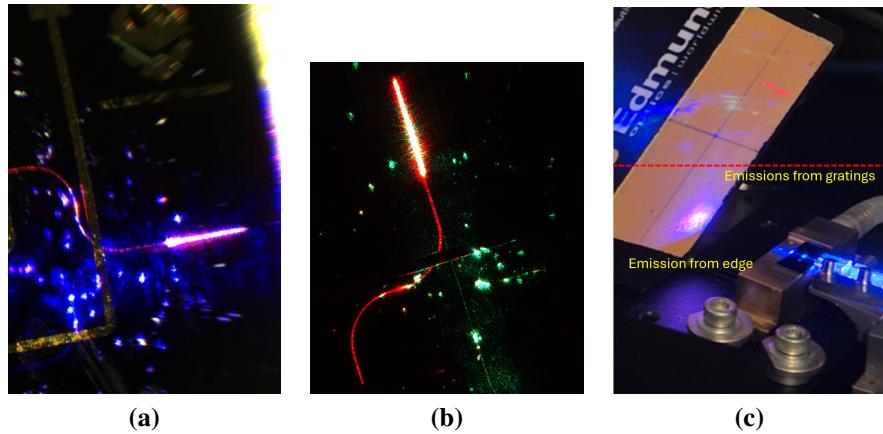


Figure 12: (a) A noticeable pink emission appears when blue and red lasers are input. (b) An orange emission is observed with red and green laser inputs. (c) Out-of-plane emission through edge waveguides, not the gratings, corresponding to the chip's output layout.



Figure 13: Multimode Grating emission pattern.

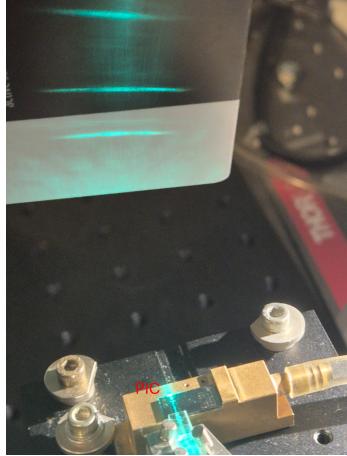


Figure 14: Coupled emission pattern from RGB gratings

Outlook

This paper demonstrates the progress made on the RGB beam combiner and outlines the current design approach. For future work, a new laboratory setup will be required to properly project the beams in the desired direction and efficiently collimate the emitted light into a CCD camera. Optical elements such as focusing lenses or cylindrical lenses will be employed to further verify and optimize the beam shape.

Experimental validation of grating efficiency and emission angles is essential, along with ensuring all waveguides are designed for single-mode operation. Improvements in fabrication precision will be necessary to achieve finer grating resolution, enabling vertical emission and minimizing unwanted angular deviations caused by foundry limitations. Such deviations can result in beam misalignment and degraded performance. Additionally, the modulation functionality needs to be validated experimentally.

Future design improvements will explore the incorporation of slanted gratings to achieve a wider field of view, potentially enabling the realization of glasses-free 3D displays [7]. Additionally, alternative modulation schemes will be investigated to further enhance system performance.

With these advancements, the RGB beam combiner holds strong potential to contribute to the development of next-generation display technologies, offering more compact, energy-efficient, and high-performance optical systems.

Acknowledgments

The author would like to acknowledge the use of fabrication and laboratory resources provided by the IOS group, led by Prof. Dr. S. M. García Blanco at the University of Twente. Special thanks to Joureñ Kortaij for assistance with laser integration. The author also gratefully acknowledges access to the MPW (multi-project wafer) service of Aluvia Photonics (<https://aluviaPhotonics.com>) and the associated laboratory support, which enabled the prototyping and testing of the device. This work was supported in part by funding from PhotonDelta and the NextGEN High-Tech Semicon. program.

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