

Holography and Photonic Integrated Circuit: an Alternative Technology for Power-Efficient Near-Eye Display Architecture

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Abstract

We present a directional display concept based on the combination of photonic integrated circuits and volume holograms. This approach, implemented in an NED architecture, could significantly improve the power consumption of Augmented Reality hardware. Comparing the 44 dB optical loss of a conventional NED design with the 18 dB of our design, we highlight the interesting potential of our display concept.

Author Keywords

Near-Eye Display, PIC, Holography, Augmented Reality.

1. Introduction

Among the most recent applications related to the field of display technologies, Extended Reality (XR) stands out as one of the most promising domains. After decades of research and developments, XR continues to capture significant attention, driven by the release of recent products and prototypes from leading industry (Apple vision pro, Meta Orion glasses ...). Regarding these developments, different technological approaches coexist, depending on the application and on the hardware limitations [1]. At the one end of the spectrum, Virtual Reality (VR) headsets immerse users in a virtual environment, with limited connection to the real world. The key parameter here is the immersive experience with high image quality displays. At the other end, Augmented Reality (AR) smart glasses overlay digital information onto the real world. The key parameter here is achieving small and efficient form factor. In between, Mixed Reality (MR) proposes digital interaction with the real world in a difficult compromise between form factor and visual experience [2].

A common challenge across these approaches is the need for power efficient display technology. Power efficiency reduces consumption and, in turn, limits heat dissipation, which is important for Near-Eye Display (NED) [3]. In the case of AR, this issue is particularly critical. Since smart glasses are used in daylight, they must be both transparent and bright. High luminance is then essential but at the expense of higher power consumption.

In this work, we propose an alternative approach to the current display technologies, aiming to pave the way for more efficient and sustainable development in NEDs. The core innovation lies in the development of a directional display that optimizes light flow within the system while minimizing the significant optical losses typically observed in conventional designs. By leveraging Photonic Integrated Circuit (PIC) technology, our approach separates the emissive component (laser) from the distributive component of the display (pixels). This separation reduces the reliance on specific rare materials, such as gallium (Ga), required in micro-LED development, contributing to both sustainability and cost efficiency [4].

In the first section, we analyze the optical losses inherent in traditional NED architectures. In section 2, we present our

concept of a directional display, explaining the principles and mechanisms underlying its improved efficiency. Finally, in section 3, we demonstrate how this innovative display can be integrated into a NED architecture, showcasing a remarkable reduction in optical losses.

2. Power efficiency in conventional NED

To analyze a conventional NED architecture, we assume a monocular device designed to project images in a single color. For this study, we adopt a pragmatic approach by selecting a Liquid Crystal On Silicon (LCOS) display as the image source and a waveguide with diffraction gratings as the combiner [5]. LCOS is a mature technology with commercially available products, offering the advantage of separating primary light emission from image sampling. It can also be paired with high-luminance LEDs to ensure bright image projection. Figure 1(a) illustrates an example of this optical architecture [6].

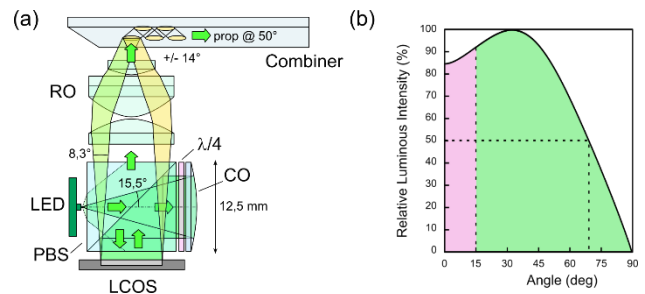


Figure 1. (a) Conventional design of LCOS light engine with a waveguide combiner. (b) Typical angular spectrum of a Mini-LED, in pink the collected optical power.

In this configuration, a LED is placed in front of a polarization beam splitter (PBS), and a concave mirror (CM) is used to collimate and reflect light toward the LCOS. Through a carefully engineered sequence of polarization rotations using quarter-wave devices, the image formed on the LCOS is directed to relay optics (RO) with optimized optical efficiency. The RO then creates a virtual image at a large distance, making it easily viewable by the user. This optical signal is then introduced into the waveguide.

We evaluated the optical losses at each step of this design, and we calculate significant photon losses at the very beginning of the architecture.

LED emission is predominantly Lambertian, stemming from the random generation of photons within the active region of the device. While this characteristic is advantageous for many applications, such as TV screens and smartphone displays, it presents a critical limitation for NEDs. Figure 1(b) shows a typical angular emission spectrum of a mini-LED [7]. In our example, the angular acceptance of the PBS, LCOS, and CM is limited to approximately 15.5°. This narrow acceptance angle captures only about 3% of the total light emitted by the LED (~15 dB loss). The following Figure 2(a) provides a detailed

breakdown of the optical losses from the light engine to the waveguide (blue bars).

Losses within the light engine itself are relatively modest, ranging between less than 1 dB and approximately 3 dB, mainly due to polarization filtering.

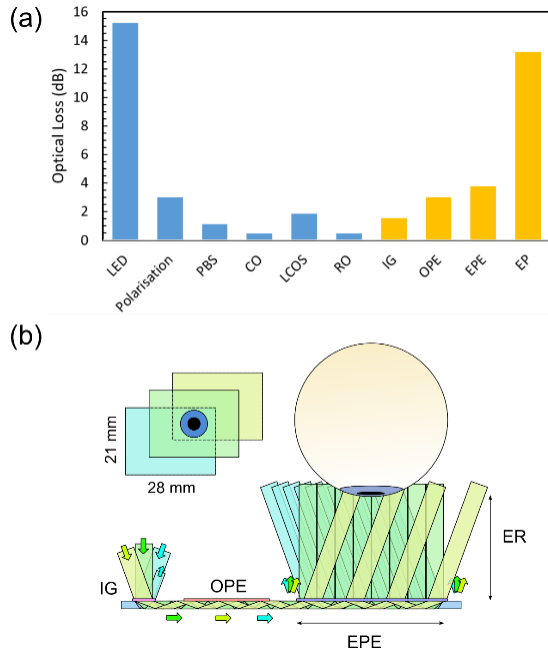


Figure 2. (a) Summary of the optical losses in the system (in blue the light engine, in yellow the waveguide). (b) Principle of the waveguide behavior with eye pupil/EPE surface discrepancy issue (inset).

As shown in Figure 2(b), the light from the LCOS is coupled into the waveguide via an input grating (IG). The waveguide uses total internal reflection to guide light, which exits toward the user’s eye at the exit pupil. Conventional designs focus on optimizing the Eye Box (EB) to ensure user comfort [8]. To achieve this, an Exit Pupil Expander (EPE) is combined with an Orthogonal Pupil Expander (OPE). These components, based on diffraction gratings, present significant design challenges. They must minimize diffraction from unwanted orders, optimize diffraction efficiency and uniformity along the EPE, and maintain transparency [6]. Additionally, the diffraction properties must be finely tuned across the grating surface. As a result, these components introduce notable optical losses, typically ranging from 1.5 dB to about 4 dB [6].

To provide an optimal field of view and Eye Relief (ER), a large EPE surface is required. The Eye Pupil (EP) captures only a small fraction of the light emitted from this large window. For instance, we estimate that less than 5% of the light emitted by the EPE (21x28 mm² in this example) reaches the retina for a 6 mm EP diameter—and this efficiency drops to only 2% for a 4 mm EP under bright daylight conditions.

In total, the optical losses across the system are staggering, amounting to approximately 44 dB. This means that only 0.004% of the light emitted by the LED ultimately impacts the user’s retina. Given this high inefficiency, we propose exploring an alternative, more sustainable display designs to address these challenges and support environmentally responsible applications for AR.

3. Directional Display concept

The analysis of optical losses in section 2 highlights two critical stages for improving efficiency: the light coupling at the beginning of the system between the LED illumination and the LCOS components and at the end of the system between the EPE and the eye. Addressing the efficiency at these two stages requires rethinking the traditional approach to NED design. Specifically, we need to move beyond the intuitive yet inefficient paradigm of free-space optics. A micro-display for NED applications should not simply be a miniaturized version of a conventional display; instead, it must represent a fundamentally different concept, designed to meet the unique demands of near-eye systems.

Contrary to LCOS and micro-LED/ OLED displays, an existing solution that is closed to meet the NED demands efficiency is Laser Beam Scanning (LBS) technology, which employs a directive laser beam deflected sequentially by two orthogonal mirrors. LBS has been integrated into various NED solutions [8-10]. However, despite its potential, LBS suffers from limitations. The raster-scan method inherently produces inhomogeneous image quality, and the use of a single laser for each color (as opposed to a laser array) often leads to speckle, further reducing image fidelity [11].

Our proposed display aims to preserve the spatial sampling properties of traditional displays while integrating the key advantage of LBS technology: its directivity. Figure 3(a) illustrates our conceptual design, where each pixel emits a beam with specified angular characteristics, defined by a divergence angle ($\beta_{i,j}$) and directionality ($\psi_{i,j}; \varphi_{i,j}$). This innovative design introduces a pixel-specific control over light emission, which is essential for achieving efficiency and high optical performance.

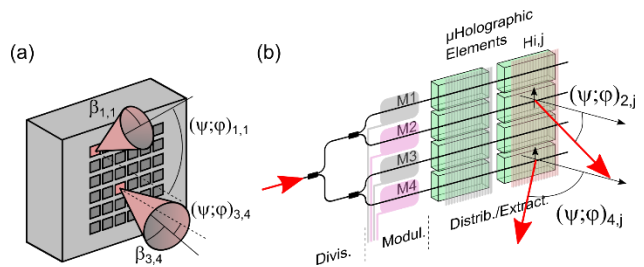


Figure 3. (a) Principle of the directive display. (b) The proposal of architecture based on photonic integrated circuit and micro holograms.

A promising technological pathway for implementing this concept leverages Photonics Integrated Circuits (PICs). As depicted in Figure 3(b), a simple PIC tree structure guides light from a laser array to the display surface. This structure comprises densely distributed waveguides that form the rows of the addressing scheme. Light is extracted column by column using switchable extraction devices. Each pixel’s value is modulated at the start of the display surface. Extracted light interacts with a volume hologram recorded at the pixel scale, which then reflects the signal with the desired divergence and directivity.

Implementing this novel approach presents several technical challenges, summarized in Figure 4, which we will detail during the conference.

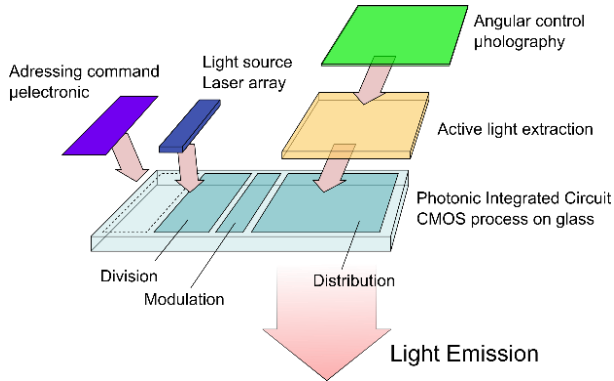


Figure 4. Summary of the general architecture of our directional display concept.

Figure 5(a) shows scanning electron microscope (SEM) images of a PIC tree structure fabricated at CEA Leti. This tree employs multimode interferometer (MMI) dividers, with single mode waveguides measuring 300 nm x 200 nm, constructed on silicon nitride (SiN) deposited over silicon dioxide (SiO₂) on a transparent substrate [12]. Figure 4(b) presents an example of a micro-hologram array with pixel sizes of 25 μm, highlighting the potential for dense and precise light control [13].

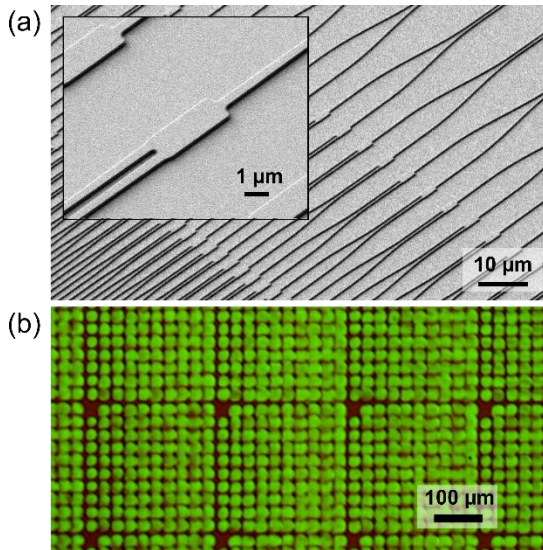


Figure 5. (a) PIC tree manufactured in CEA Leti. (b) Micro holograms recorded in CEA Leti .

4. Implementation in NED system

Addressing the challenge of pupil loss reduction requires abandoning the traditional pupil expansion schemes in favor of a design that confines the EB volume to the precise location of the eye's pupil. One potential solution involves the use of a free-space holographic combiner, as illustrated in Figure 6. In our proposed design, the display is positioned near the focal point of the off-axis combiner, with each pixel coding a directivity toward the point A. The spatial arrangement of the pixels on the display determines the direction of the corresponding signal within the field of view, forming an image at a large distance.

The pixel directivity ensures that the field of all pixels converge

toward the same point B, which is the optical image of point A as formed by the combiner. Point B is designed to coincide with the average location of the user's eye pupil. The divergence of the pixels controls the size of the EB.

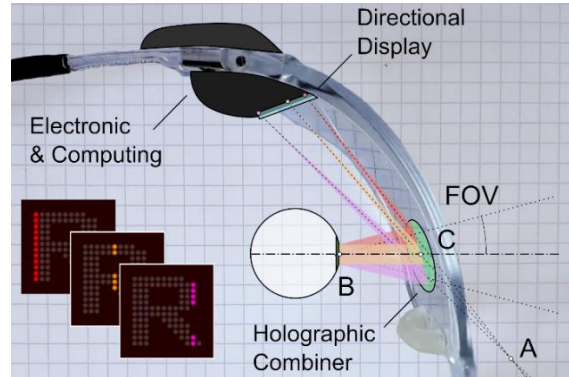


Figure 6. Principle of our optical architecture with an example of sequential column addressing.

This optical architecture offers the flexibility to adjust device efficiency based on the requirements of the application (location and size of one or multiple EBs) [14].

Unlike traditional displays, light generation in our design is localized at the system's source rather than being distributed across the display surface. To maintain compatibility with the photonic integrated circuit (PIC) design, we use high-directivity light sources, such as superluminescent LEDs (SLEDs) or laser arrays [15].

Figure 7 illustrates the optical efficiency at each stage of the system.

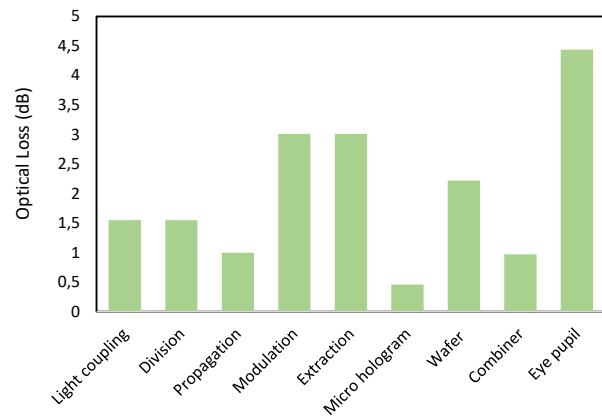


Figure 7. Summary of the optical losses in the directional display system.

The efficiency of our directional display is distributed within the system as follows:

- The coupling efficiency of light from the source into the PIC is the first source of loss in the system. Recent research reports light coupling efficiencies approaching 70% [16], offering a promising starting point.
- Losses within the PIC are relatively low. Multimode interferometers (MMIs) are expected to achieve efficiencies

better than 0.2 dB, and waveguides are anticipated to exhibit losses of about 1 dB/cm in visible spectrum [17].

- For light modulation and extraction, technological advancements are ongoing. A reasonable estimate suggests losses of approximately 3 dB at these stages.
- Micro-holograms within the system demonstrate high efficiencies, nearing 90%, while the reflected signal passing through the transparent substrate incurs minimal losses.
- The efficiency of the holographic combiner is optimal when the angular and spectral emission of the light source matches the selectivity of the hologram.
- The final loss is associated with the trade-off made for the EB. For an EB diameter of 10 mm and an eye pupil diameter of 6 mm, the estimated loss is 4.4 dB. This increases to 8 dB for a 4 mm pupil diameter.

In total, the proposed system demonstrates optical losses of approximately 18 dB, representing an improvement of more than two orders of magnitude over the aforementioned design. Despite this significant enhancement, 98.5% of emitted photons are still lost within the system. Future efforts should focus on further advancements in PIC technologies, particularly in areas such as light coupling efficiency, waveguide propagation losses, and modulation methods.

5. Conclusion

In this contribution, we propose a novel architecture in NED design, leveraging the integration of photonic integrated circuits and holography. The confined nature of light propagation within the PIC, combined with the high efficiency of holographic elements, offers significant advantages in power efficiency compared to conventional approaches utilizing mini-LED or micro-LED technologies. Our analysis estimates a total optical loss of approximately 18 dB, representing an improvement of over two orders of magnitude compared to designs based on LCOS and diffractive waveguides.

This approach separates the light source from the pixel distribution, which minimizes reliance on rare materials such as gallium, commonly used in micro-LED displays. This design not only enhances efficiency but also supports a more sustainable development for NED technologies.

While our analysis demonstrates promising results, we recognize the need to consider additional performance criteria, such as field of view, image resolution, display latency, and production cost. These factors are essential for a comprehensive evaluation of the proposed system. We look forward to discussing these considerations further during the conference and exploring the potential of this approach to reshape the future of NED design.

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