Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Optimization of Diffraction Efficiency of a Holographic Demultiplexer for the Optical Transmission Windows at 1310 nm and 1550 nm

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Holographic demultiplexers are critical components of contemporary optical communication systems, allowing for effective wavelength separation while minimising losses. This study focusses on improving the diffraction efficiency of a single holographic demultiplexer designed for the popular two optical transmission windows at 1310 and 1550 nm. Unlike conventional wavelength demultiplexing technologies, which depend on bulky and expensive dielectric filters or gratings, holographic demultiplexers are small, cost-effective, and highly efficient alternatives. Key parameters such as grating period, recording geometry and material refractive index modulation are optimized to maximize performance at the desired wavelengths. Simulation findings show that the maximum diffraction efficiency at transmission windows 1310 and 1550 nm is over 95%, with little crosstalk and insertion loss. This study is unique in that it uses a dual-wavelength optimization technique to provide consistent performance in two critical transmission windows, allowing smooth integration to optical system. Compared to conventional methods, the suggested holographic demultiplexer has higher scalability, lower manufacturing complexity, and better flexibility for high-speed optical networks. This study illustrates how holographic optical components can revolutionize wavelength demultiplexing, paving the way for more efficient and compact optical communication systems. Future efforts will focus on experimental validation and integrating these devices into fully operational photonic circuits.

Keywords: Holographic Demultiplexer, Holographic Optical Elements, Diffraction Efficiency, Optical Transmission Windows.

1. Introduction

The development of Holographic Optical Elements (HOEs) has a significant impact on optical communications by providing much smaller, lighter, and efficient alternatives to conventional optical components. Function of HOEs are based on diffraction principles. Diffraction efficiency of such HOEs is given by Kogelnik's coupled-wave theory, which provides a solid framework for understanding the behaviour of thick holographic gratings [1]. Compared to common optical components such as dielectric filters and gratings, HOEs offer greater functionality and flexibility for design [2], [3]. Holography, a flexible optical technique, has advanced greatly since its conception, allowing a wide range of applications in scientific and technological fields. HOEs are effective devices for beam steering, focusing, and wavelength multiplexing. Hariharan's work extensively covers the fundamental ideas and practical processes of holography leading to the groundwork for a solid understanding of HOE operational mechanisms and manufacturing processes [4]. Pappu analysed the development and capabilities of HOEs in a two-part series. The first part of this paper highlights the fundamental properties of HOEs, including their optical efficiency, angular sensitivity, and wavelength selectivity, which make them superior to conventional optical elements for a variety of photonic applications [5]. The second part expands on cutting-edge innovations in HOE fabrication, emphasizing its versatility and compactness for integration into current optical systems [6]. The optimisation of HOEs for certain capabilities, such as beam concentration and diffraction efficiency, has received a lot of attention. Shekhar and Yadav discovered the relationship between diffraction efficiency and the angle of illumination light, providing important insights on holographic concentrator design. Their findings highlight the relevance of angular factors in achieving peak performance in holographic applications [7]. Recent advances in HOEs have been focused on their use in wavelength-specific optical systems. For example, the use of holographic directional couplers for various optical transmission windows, including operating wavelengths 1310 nm and 1550 nm – for optical communications – has demonstrated the potential of HOEs to improve system efficiency and reduce losses compared to conventional coupling elements [8]. Advances in HOE have a great impact on optical communications, particularly on the design and execution of demultiplexers. Shimizu et al. developed a volume holographic spatial mode demultiplexer using a dual wavelength approach, proving its ability to effectively manage spatial mode splitting in advanced optical systems [9]. Similarly, an experimental demonstration of a holographic demultiplexer with low polarisation-dependent loss using a long-period diffraction grating marked a milestone in reducing signal degradation and enhancing system reliability. The study of angularly multiplexed volume holograms has broadened the applications of holographic demultiplexers. Subsequently, Wakayama et al. built a mode demultiplexer [10]. Mahros and Eshri built a fiber-based simultaneous mode and wavelength demultiplexer, demonstrating its flexibility and applicability to integrated photonic systems [11]. Holographic design optimizations have also made it easier to fabricate multimode fiber demultiplexers. Ishii and Kubota showed a wavelength demultiplexer using optimized HOE to effectively regulate light propagation in multimode fiber, resulting in increased diffraction efficiency and minimal cross-talk [12]. K. Morita et al. developed a volume holographic wavelength demultiplexer using rotation multiplexing in a 90° geometry, providing a small and scalable solution for wavelength-specific applications [13,14]. Finally, de Schryver's early contributions to the fabrication of holographic optical element wavelength multi-demultiplexers in the near-infrared region paved the way for further advances, demonstrating the ongoing importance of holographic methods in optical engineering [15]. These developments demonstrate the efficiency and potential of HOEs as an adaptable solution in wavelength-selective applications.

Figure 1 shows the use of a laser diode as a light source that emits multiple optical signals of different wavelengths. These signals are directed through a multimode fiber (MMF), which serves as the transmission medium. The optical signals from the MMF are directed to a holographic demultiplexer (HL_1)which performs wavelength-specific separation. This setup ensures effective spectral separation and routing for applications requiring wavelength-division multiplexing (WDM) technology.

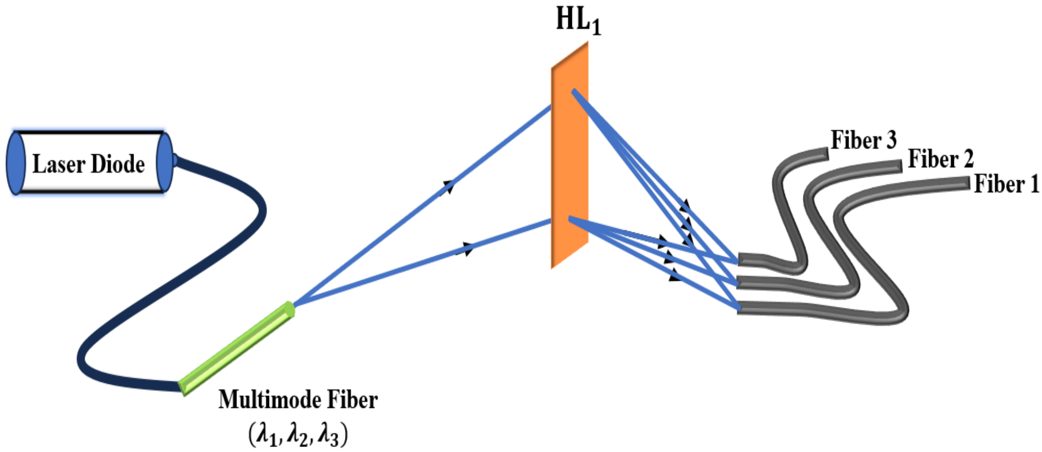

Figure 1: Schematic diagram of holographic demultiplexer

This study advances these basic researches to improve the diffraction efficiency during critical communication windows. The goal of this work is to optimize the recording conditions and material configurations for holographic demultiplexers using computational models and physically confirmed parameters. The findings are expected to significantly contribute to the development of next-generation optical networks by improving bandwidth utilization and dependability. The suggested technique not only emphasizes the superiority of HOEs over conventional optical elements, but it also addresses the growing need for scalable, high-performance photonic components in current optical communication networks.

2. Theoretical Analysis of Diffraction Efficiency for Holographic Demultiplexers

The design and optimization of holographic demultiplexers for optical transmission windows requires achieving high diffraction efficiency at the desired wavelengths, especially 1310 and 1550 nm. These wavelengths correspond to the common optical communication bands. To maximize the efficiency, thick-phase holographic gratings are used with optimized parameters such as film thickness (d), refractive index modulation depth (n), and fringe spacing (Λ). The coupled wave theory [1] gives a mathematical framework to analyze the diffraction efficiency (η) of volume phase transmission holograms by taking into account the sinusoidal refractive index modulation and deviation from the Bragg angle (θ_B) during reconstruction. The diffraction efficiency is described as:

$$\eta = \frac{\sin^2(\xi^2+\nu^2)^{1/2}}{(1+\frac{\xi^2}{\nu^2})} \tag{1}$$

Where the parameters ξ and ν are represented as

$$\xi = \delta \frac{2\pi n}{\lambda} \, d\sin\theta_B \quad (2)$$

And

$$N = \frac{\pi \Delta n d}{\lambda \cos\theta_B} \quad (3)$$

Here, δ denotes the angular deviation from the Bragg angle (θ_B). Precise control of these parameters results in enhanced diffraction efficiency, which is crucial for demultiplexer performance.

The relation between fringe spacing (Λ) and Bragg angle (θ_B) in a hologram is as follows:

$$\mathrm{Sin}\theta_B = \frac{\lambda}{2n\Lambda} \quad (4)$$

and

$$\mathrm{Cos}\theta_B = \sqrt{1 - \left(\frac{\lambda}{2n\Lambda}\right)^2} \quad (5)$$

When illumination is made at ($\delta = 0$) and wavelength of reconstructing wave satisfies Bragg's condition, the η can be represented as:

$$\eta = \sin^2 \upsilon \quad (6)$$

$$\eta = \sin^2\left(\frac{\pi \Delta n d}{\lambda \cos\theta_B}\right) \quad (7)$$

$$\eta = \sin^2 \left(\frac{\pi \Delta n d}{\lambda\left\{1 - \left(\frac{\lambda}{2n\Lambda}\right)^2\right\}^{\frac{1}{2}}} \right) \quad (8)$$

2.1 Simulation results

To optimize the performance of the holographic demultiplexer in the optical windows at 1310 nm and 1550 nm, the diffraction efficiency has been investigated under different conditions. Figure 2 shows how diffraction effectiveness increases with film thickness for on-Bragg illumination while retaining constant $\Delta n = 0.0265$, and fringe spacing $\Lambda = 1.666\,\mu m$. Figure 3 illustrates the change in optimum efficiency towards higher wavelengths when Δn rises, with $d = 20\mu\,m$ and $\Lambda = 1.666\mu m$ remained constant. Figure 4 shows how variation in fringe spacing affect diffraction efficiency under constant conditions $\Delta n = 0.0265$ and $d = 10\mu m$.

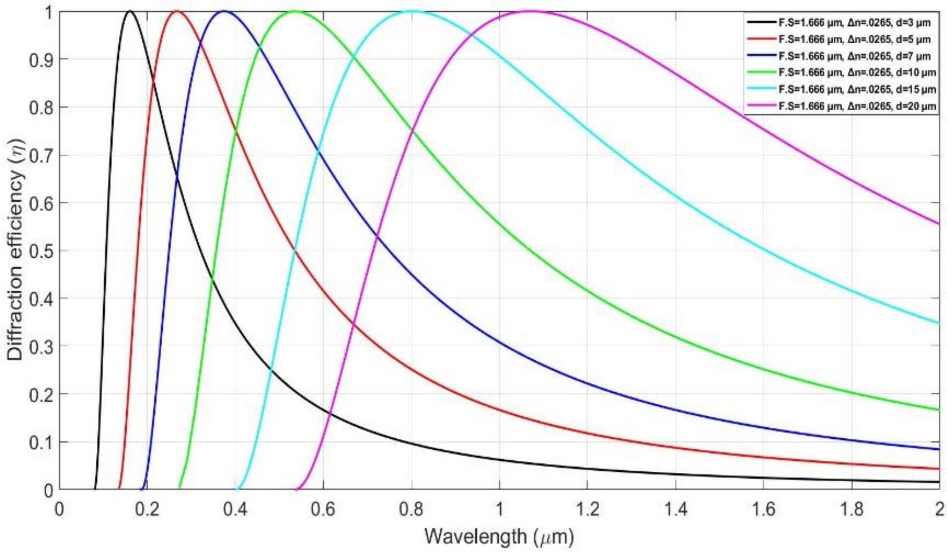

Figure 2. Simulation result of (η) vs. (λ) for variable (d) with constant index modulation depth ($\Delta n = 0.0265$) and fringe spacing ($\Lambda = 1.666$ µm).

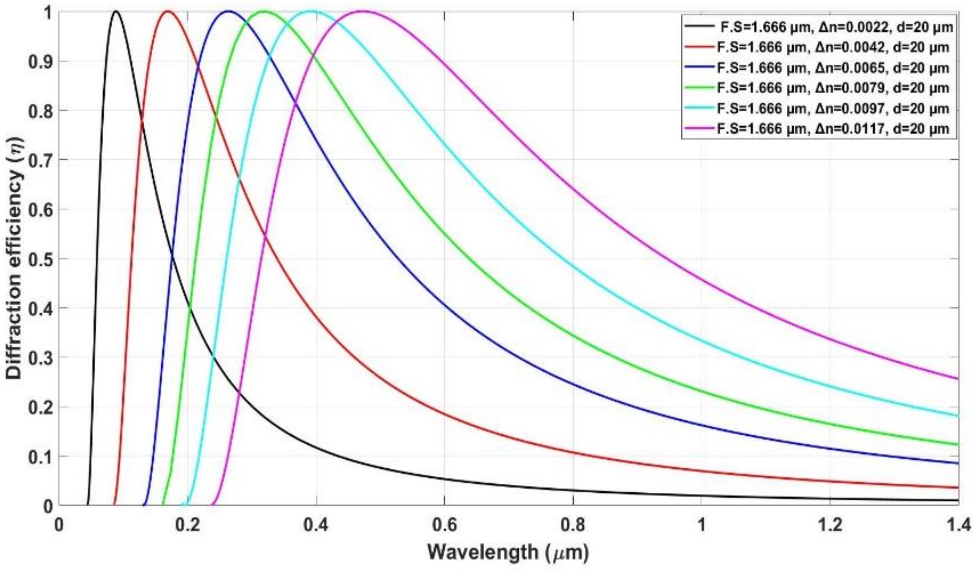

Figure 3. Simulation result of (η) vs. (λ) for variable (Δn), with film thickness ($d = 20$ µm) and fringe spacing ($\Lambda = 1.666$ µm) constant.

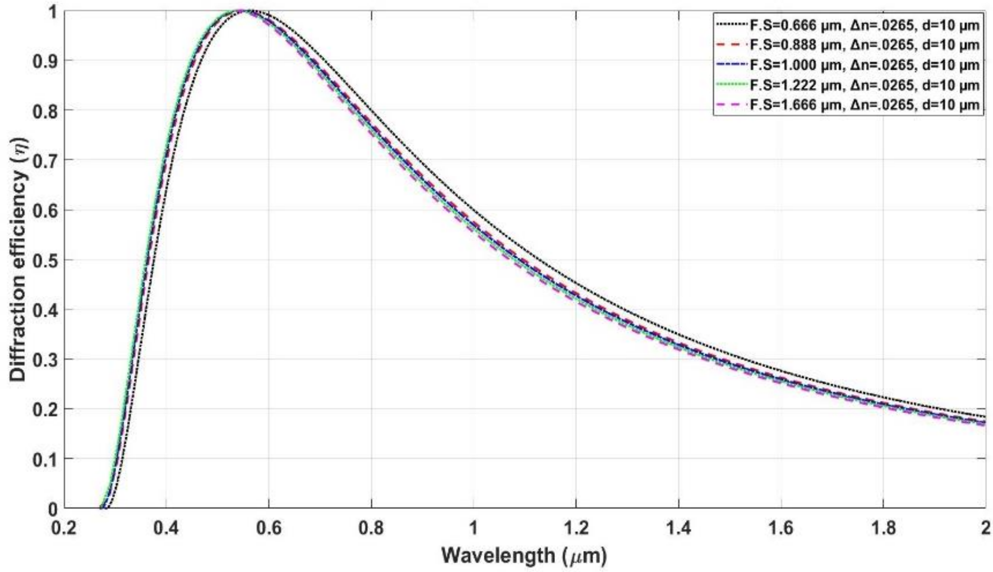

Figure 4. Simulation result of (η) vs. (λ) for variable (ʌ), with film thickness ($d = 10$ μm) and index modulation depth ($\Delta n = 0.0265$) constant.

Finally, the demultiplexer was optimized to operate at two major optical windows ($1300 - 1350$ nm and $1500 - 1600$ nm), resulting in high diffraction efficiency for practical communication applications. Figure 5 depicts the findings, demonstrating the ability of the design to maintain a diffraction efficiency of approximately 95% at both the 1310 nm and 1550 nm transmission bands.

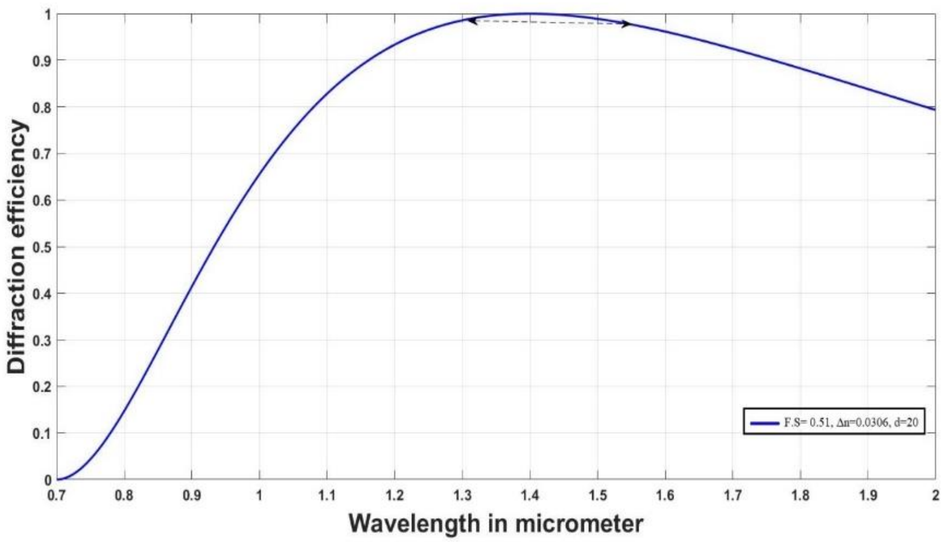

Figure 5: Simulation result of (η) vs. (λ) for a holographic demultiplexer ($d = 20$ μm, $\wedge = 0.51$ μm, $\Delta n = 0.0306$) at 1310 nm and 1550 nm.

3. Experimental

3.1 Configuration for Recording and Playback of Holographic Demultiplexer

To produce the holographic demultiplexer, a spherical wavefront from a point source was used to interact with another coherent spherical wave from the same source on a high-resolution photosensitive film. The resulting interference pattern generates an off-axis zone plate, also known as a holographic lens. The exposed film underwent regular developing and repair operations. For this work, $\mathrm{PFG}-01$ high-resolution silver halide film was used. This film is sensitive to a wavelength of $\lambda = 0.6328\,\mu\mathrm{m}$ (red wavelength), has a resolution of $3000\,\mathrm{lines/mm}$ and an average grain size of $40\,\mathrm{nm}$, making it perfect for recording the holographic lens. A $10\,\mathrm{mW}$ He-Ne laser was used as the coherent light source. A beam splitter divided the laser beam into two equal parts: reflected and transmitted. To illuminate the recording film with spherical wavefronts, one of the beam was made to passed through a $5\,\mu\mathrm{m}$-diameter pinhole. At the same time, the other beam was also processed as shown in figure -6 to obtain another spherical wavefront. These both spherical waves simultaneously illuminated the light-sensitive material, resulting in an ideal holographic demultiplexer. An important aspect of the recording process was to maintain equal path lengths for the reflected and transmitted rays to ensure timely coherence. Figure 6 schematically depicts the recording geometry of the proposed holographic demultiplexer.

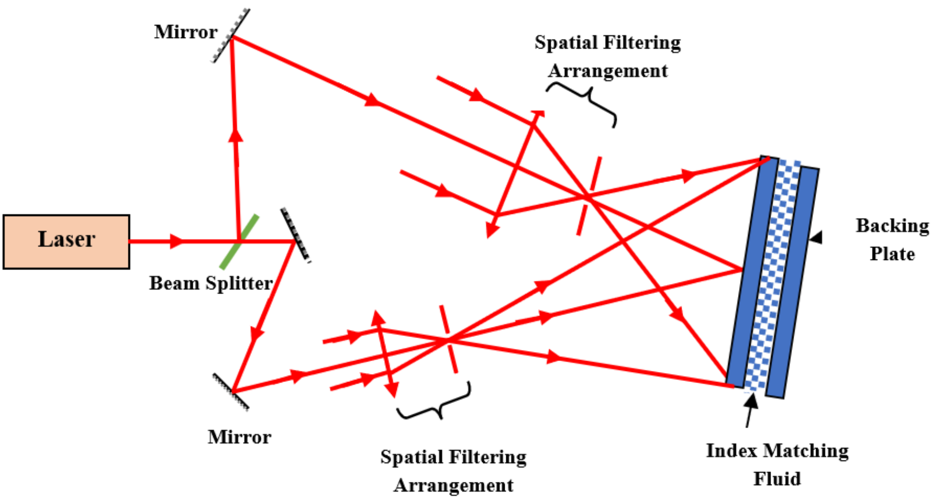

Figure 6: Schematic diagram of the setup for recording the holographic demultiplexer.

3.2 Playback geometry of the recorded holographic demultiplexer

Figure 7 shows the playback arrangement for realizing the function of a holographic demultiplexer. In this configuration, the holographic lens is illuminated by a suitable spherical wavefront of coherent light to generate another spherical converging wave front identical to that of recording wavefront .The diffraction efficiency of the demultiplexer recorded with optimized parameters was measured at wavelengths corresponding to the major optical communication windows ($\lambda = 850\,\mathrm{nm}, 1310\,\mathrm{nm}, \text{and } 1550\,\mathrm{nm}$). Figure 8 shows that the experimental diffraction efficiency curves which closely matches with theoretical predictions. The holographic demultiplexer demonstrated enhanced diffraction efficiency, stable performance across multiple datasets, and optical transmission capabilities at critical wavelengths. This demonstrates the design's ability to handle optical signals in communication networks.

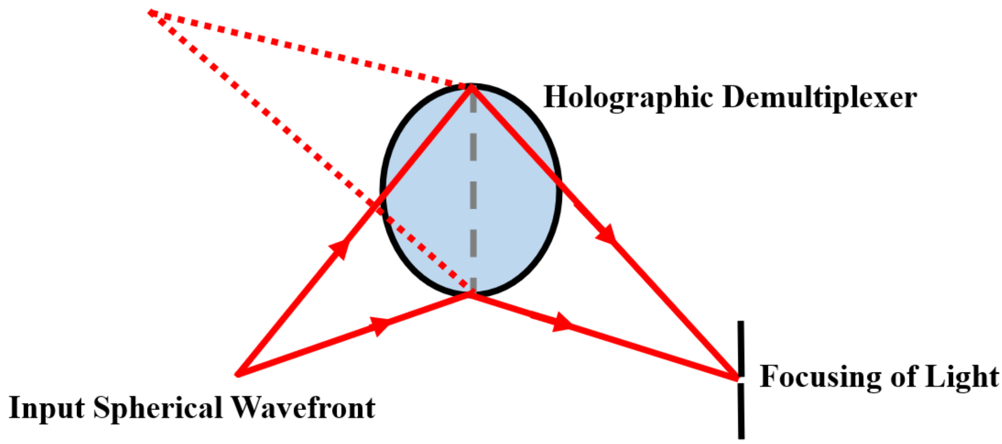

Figure 7: Playback configuration of the holographic demultiplexer under spherical wavefront illumination.

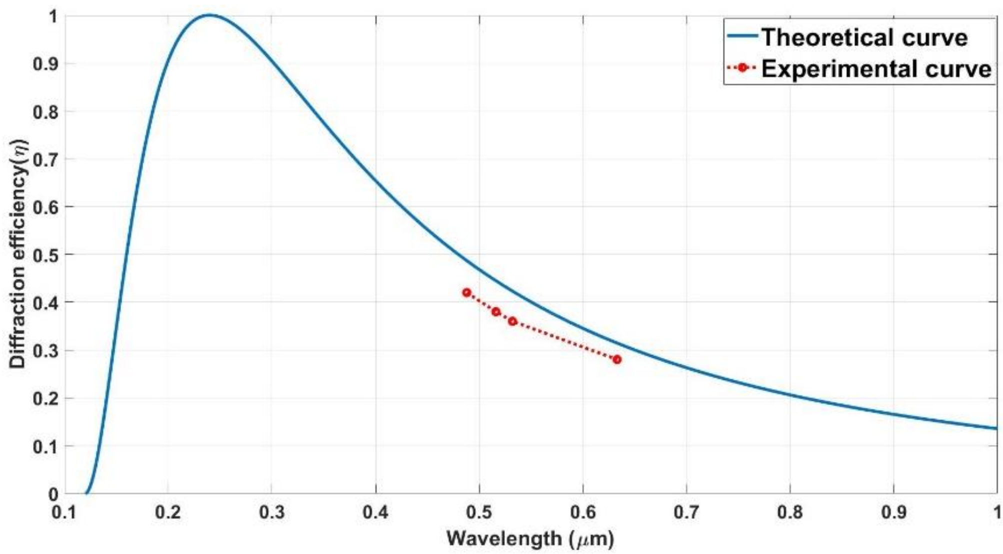

Figure 10: Experimental and theoretical comparison of (η) vs(λ) for the optimized holographic demultiplexer for $d = 20\ \mu m, \Lambda = 0.51\ \mu m$, and $\Delta n = 0.0306$.

4 Conclusion

This paper describes the successful design, fabrication, and experimental validation of a holographic demultiplexer tuned for optical transmission windows at 1310 and 1550 nm. The suggested demultiplexer is very accurate and coherent in driving certain wavelength bands, making it ideal for dense wavelength-division multiplexing (DWDM) systems in current optical communication networks. The experimental findings, supported by theoretical models, demonstrate the durability of the holographic recording technique in achieving precise optical modulation and diffraction features. The playback setup successfully generated the recorded wavefront, demonstrating the ability to focus different wavelengths at different locations with reasonably good diffraction efficiency. Moreover, it was important to optimize the recording parameters such as exposure length, spatial filtering, and beam alignment to achieve high performance. The results of this study highlight the promise of holographic optical elements in manufacturing small, efficient, and cost-effective components for next-generation photonic systems. Future research may consider the use of new light-sensitive materials and multichannel holographic recording to improve the performance and scalability of holographic demultiplexers in high-capacity optical networks.

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