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Design and Analysis of Laser to Fibre Coupling System Using Holographic Optical Element

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This paper focuses on design of cost effective, light – weight holographic coupler to couple laser light to optical fibre with reasonably appreciable diffraction efficiency. Optimization of film thickness (d), index modulation depth $(\Delta \mathrm{n})$ and fringe spacing $(\wedge)$ have been made to design holographic optical element recorded in high resolution silver halide film $(\mathrm{PFG}-01)$ for achieving maximum coupling efficiency for Laser-to-Fiber coupling systems within specific optical windows. A theoretical investigation has been conducted under the light of coupled wave theory-based formula to analyze the variation in diffraction efficiency with wavelength for different values of 'd', $\Delta \mathrm{n}$ and $\wedge$. Theoretical analysis revealed that for on-Brag illumination, diffraction efficiency of recorded hologram does not changes significantly with change in fringe spacing hence optimization of thickness (d) and refractive index modulation depth (Δn) for a fixed fringe spacing to achieve peak efficiency for transmission window $1310\,\mathrm{nm}$ and $1550\,\mathrm{nm}$. was made. The results on optimization of parameter 'd' and $\Delta \mathrm{n}$ to achieve a single laser to fibre coupler for the two optical windows $1250{-}1350\,\mathrm{nm}$ and $1500{-}1600\,\mathrm{nm}$, operating at $1310\,\mathrm{nm}$ and $1550\,\mathrm{nm}$ respectively are presented. The paper also discusses the advantages on use of Holographic Optical Elements (HOEs), such as lightweight, thin-film geometry, cost-effectiveness, and ease of fabrication. The paper also emphasizes on role of use of HOEs in technological advancement of optical communication for real world application.

Keywords: Holographic optical element, Holographic coupler, Diffraction efficiency, Laser to fiber coupling

1 Introduction

The rapid advancement of optical fiber communication technologies involves the creation of effective coupling techniques to improve optical system performance. Optical fiber communication (OFC) has emerged as an alternative to traditional copper wire transmission due to its capacity to transfer messages over substantially longer distances with low power loss and vulnerability to electromagnetic interference (EMI). The use of optical fibers has revolutionized communication technology by providing unparalleled benefits such as extremely high bandwidth, signal transmission over longer distances with low attenuation, EMI resistance, highly secure data transmission, and a lightweight, compact size that makes it easier to accommodate increasing bandwidth demands. Now-a-days optical fiber is used widely to create a communications infrastructure. Optical systems are powered by a modulated light source fed into the fiber and sent to the receiver. The receiver then decodes the optical signal and transfers it to desired location. The real-world application of optical fiber system is more sophisticated than previously suggested. Most communications are bidirectional, requiring a transmitter and receiver at each end of the fiber with advance tools. The light source, the laser/LED, must be aligned with the fiber to ensure that the output signal is captured efficiently. When transmitting light through the fiber, proper alignment and mechanical tolerances must be addressed. HOEs have gained popularity due to their precise light manipulation capabilities, which are useful in designing Multiplexor, DE multiplexor, fiber to fibre coupler and holographic laser-to-fiber (LF) coupling systems. Optimizing these systems is critical for obtaining high coupling efficiency, which is an essential component of advanced OFC architecture. The design and implementation of holographic LF coupling systems that use HOEs, such as holographic lenses (HL), represents a significant advancement in OFC. These systems can improve LF coupling operations in optical fiber networks by using unique properties of HOEs, such as their ability to control light

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with accuracy and efficiency while avoiding monochromatic aberrations.

Holography, invented by Dennis Gabor, revolutionized optical science by enabling the holographic recording and reconstruction of light wave fronts[1]. In technological advancements of the real-world, use of holography and HOEs have grown tremendously in recent years, including the invention of refractive elements or diffractive components (HL) and couplers. These diffractive optical components, as defined by Saxby, have features such as lightweight, thin film size, and low cost, making them perfect for incorporation into modern OFC systems[2]. The tuning of the three recording and processing parameters namely film thickness(d), index modulation depth(Δn), and fringe spacing(Λ) are critical to enhance the efficacy of LF couplers. Optimization of these parameters is essential for maximizing coupling efficiency at optical transmission windows, particularly within the optical windows of $1250-1350\,nm$ and $1500-1600\,nm$, which are critical for fiber-optic communications[3,4]. Silver halide media, with an average refractive index of $n = 1.54$, are widely used for recording diffractive component due to their high resolution and greater sensitivity[5]. The coupled wave theory, introduced by Kogelnik, provides a theoretical framework for understanding and predicting the behaviour of holographic gratings under different conditions[6]. Utilizing these theoretical insights, researchers have extensively studied as to how variations in film thickness, index modulation depth, and fringe spacing affect diffraction efficiency and overall system performance[7-9]. Experimental setups for recording holographic lenses typically involve precise arrangements to ensure the aberrations free formation of interference patterns. These patterns are crucial for creating effective holographic lenses capable of focusing and coupling light efficiently. Advanced holographic techniques enable the production of HLs with high diffraction efficiency, as demonstrated in studies comparing experimental results with theoretical predictions. Previous research has shown that HLs have a wide range of real world applications, including beam shaping, optical interconnects for VLSI, and holographic head-up displays[10-12]. These works demonstrate the adaptability of holographic optical components for manipulating light propagation and its distribution with high efficiency. Furthermore, advances in designing processes have permitted the researchers of high-quality HLs with customizable features to meet specific needs of modern communication system. Recent advancements in development process have made it possible to produce these HOEs in mass-produce through replication techniques leading to enhanced accessibility for commercial applications[13-15]. The versatility and scalability of holographic lenses, position them as superior alternatives to conventional optical elements, especially in optical fiber communication systems where weight, cost, and performance are considered to be the critical considerations. Recent advances in holographic and diffractive optics have resulted in significant improvements in laser-to-fiber coupling systems. HOEs have been constructed and modelled for beam-coupling applications at a wide range of incident angles, improving angular bandwidth and diffraction performance[16]. Wavelength-multiplexed volume holographic couplers have also been developed to improve spectral channel separation and beam concentration[17]. Diffractive optical components have been shown in reviews to be small, lightweight, and capable of broadband functioning in free-space communication and imaging systems[18]. Studies on the fabrication and performance of several holographic lenses show control over aberrations and focus quality[19]. Holographic demultiplexers optimized for multimode fibers and couplers specifically designed for monomode fibers have shown promising fiber integration results[20,21]. Furthermore, strategies to improve the coupling efficiency in single-mode fibers using improved lens geometry and the use of correct microlens profiles for effective fiber alignment[22,23]. These contributions form the basis for current developments in holographic coupling systems.

The primary scientific contributions of this work describe a unique and experimentally proven method for improving laser-to-fiber coupling efficiency with a dual holographic lens (HL)-based system. The primary scientific achievements include the development and optimization of a low-cost, miniaturized HOEs recorded on a high-resolution silver halide medium. The influence of important factors such as film thickness, fringe spacing, and refractive index modulation depth on the diffraction efficiency was studied using Kogelnik's coupled wave theory. The optimized arrangement exhibits good coupling performance with excellent theoretical and experimental stability in two primary optical communication windows $(1250-1350\,nm$ and $1500-1600\,nm)$. Furthermore, the study shows that HOEs outperform conventional optics in terms of alignment tolerance, manufacturing simplicity, and scalability, which has fascinating implications for future integrated photonic systems.

Figure 1 shows the schematic arrangement of the proposed holographic LF coupling system. It includes a spatial filtering arrangement to remove unwanted aberrated optical signals, which guarantees that the optical signal produced by the spatial filter arrangement (SFA) is free from any defect. The two-HL system is designed to efficiently couple laser light into the core of an optical fiber.

This study focuses on the optimization of film thickness, index modulation depth, and fringe spacing in the development of an LF coupler consisting of two holographic lenses (HLs). Section 1 provides an introduction and the optical design considerations required to achieve high-efficiency functioning of the proposed two-HL system for LF coupling. Section 2 describes the experimental studies and setup used to develop the proposed system. The study attempts to improve the efficiency of laser-to-fiber coupling devices. The findings, as summarized in Section 3, are presented to greatly enhance optical communication technology, providing insights that can lead to the creation of more efficient and cost-effective solutions.

1.1 Theoretical Analysis LF Coupling Systems Across Desired Wavelength Ranges

For high coupling efficiency, a holographic LF coupler requires a thick-phase holographic lens system capable of transmitting modulated laser signals between fiber ends with higher efficiency. The main recording and processing parameters, namely film thickness, refractive index modulation depth and fringe spacing, are optimized to achieve maximum efficiency at the transmission wavelength. Coupled wave theory[6] provides a mathematical formula for the diffraction efficiency (η) of a volume phase transmission hologram. This concept is based on the sinusoidal modulation of the refractive index within the recording material. Coupled wave theory describes the diffraction efficiency of a volume phase transmission hologram, allowing for deviations from the Bragg angle during reconstruction, as follows:

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

Where the parameters ξ and ν are represented as

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

And

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

where δ is the angle of deviation from Bragg angle θ_B. This formula emphasizes the significance of exact control over these parameters for effective coupling. Using modern laboratory techniques and thorough design considerations guarantees that the holographic coupler performs successfully over the necessary wavelength range, resulting in considerable advancements in optical communication systems. Relation between (Λ) recorded in the hologram and $(\theta_B)$is given as:

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

and

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

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

$$\eta = \sin^2 \upsilon \quad \text{... (6)}$$

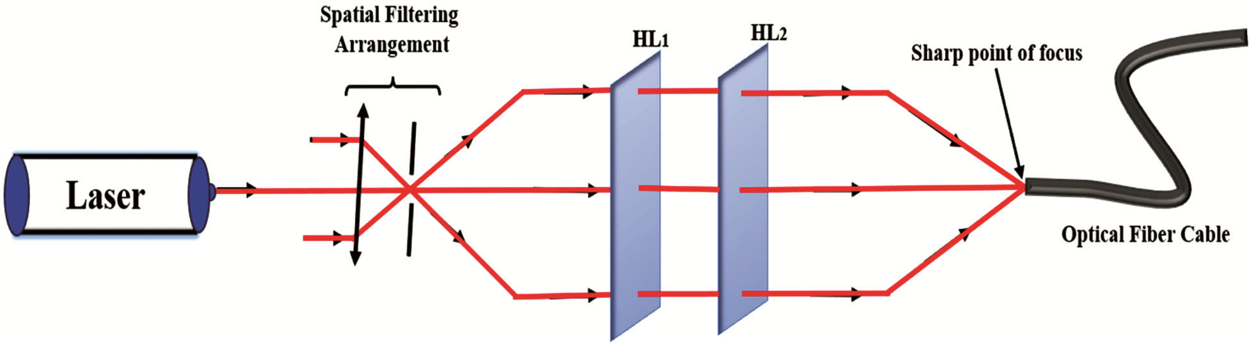

Fig. 1 — Schematic representation of holographic LF coupling system

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

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

The curves presented in Fig. 2 have been generated using equation (8), which shows how diffraction effectiveness varies with film thickness for illumination at the on-Bragg angle while keeping the refractive index modulation depth ($\Delta n = 0.0265$) and fringe spacing ($\Lambda = 1.666\ \mu m$) constant. Figure 3 shows the shift in optimal efficiency operation towards higher wavelengths with increasing refractive index modulation depth while keeping a constant fringe spacing ($\Lambda = 1.666\ \mu m$) and film thickness ($d = 20\ \mu m$). Figure 4 shows how altering fringe spacing (Λ) affects diffraction efficiency for a given refractive index modulation depth ($\Delta n = 0.0265$) and film thickness ($d = 10\ \mu m$). In a thick-phase transmission hologram optimized for maximum efficiency at a desired wavelength under on-Bragg illumination, changes in fringe spacing (Λ) do not significantly affect diffraction efficiency with variations in the reconstruction wave wavelength, provided the film thickness and refractive index modulation remain constant (Fig. 4).

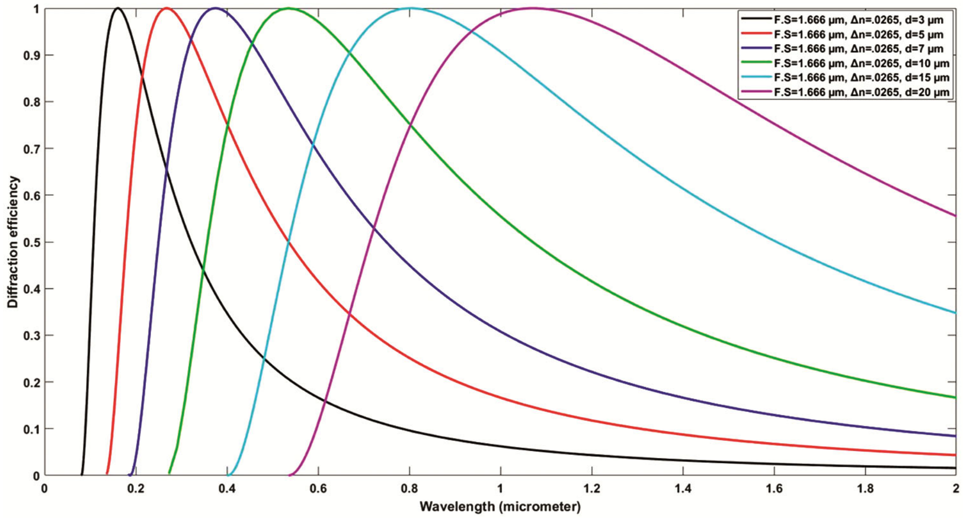

Fig. 2 — Simulation result of (η) vs. (λ) for variable (d) with constant index modulation depth ($\Delta n = 0.0265$) and fringe spacing ($\Lambda = 1.666\ \mu m$)

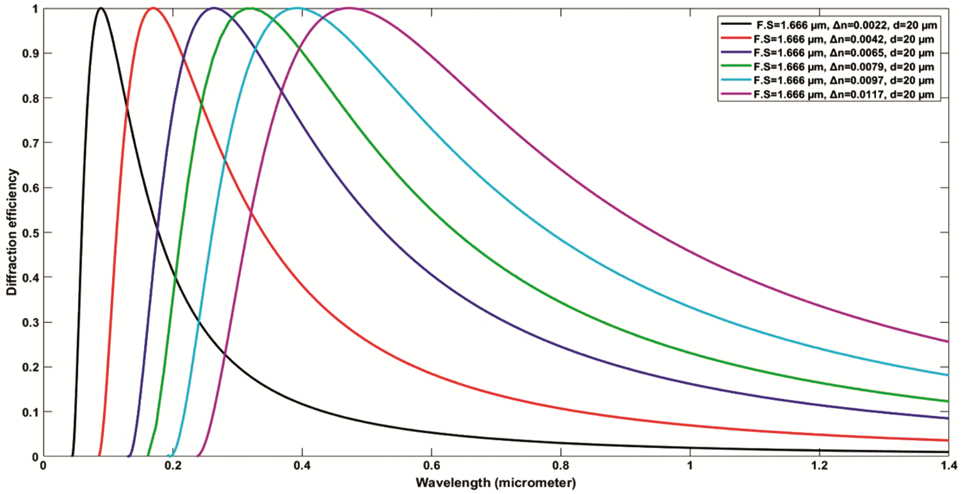

Fig. 3 — Simulation result of (η) vs. (λ) for variable (Δn), with film thickness ($d = 20\ \mu m$) and fringe spacing ($\Lambda = 1.666\ \mu m$) constant

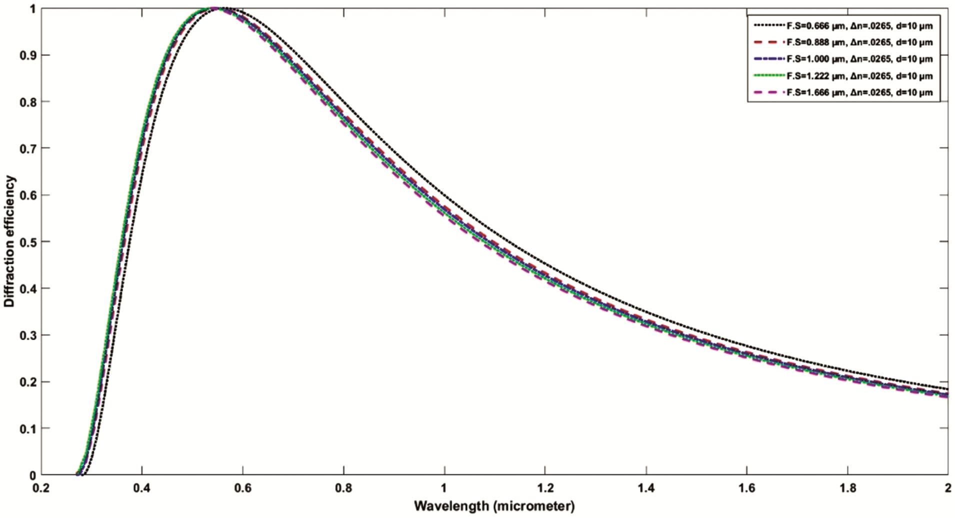

Fig. 4 — Simulation result of (η) vs. (λ) for variable (ʌ), with film thickness (d = 10 μm) and index modulation depth (Δn = 0.0265) constant

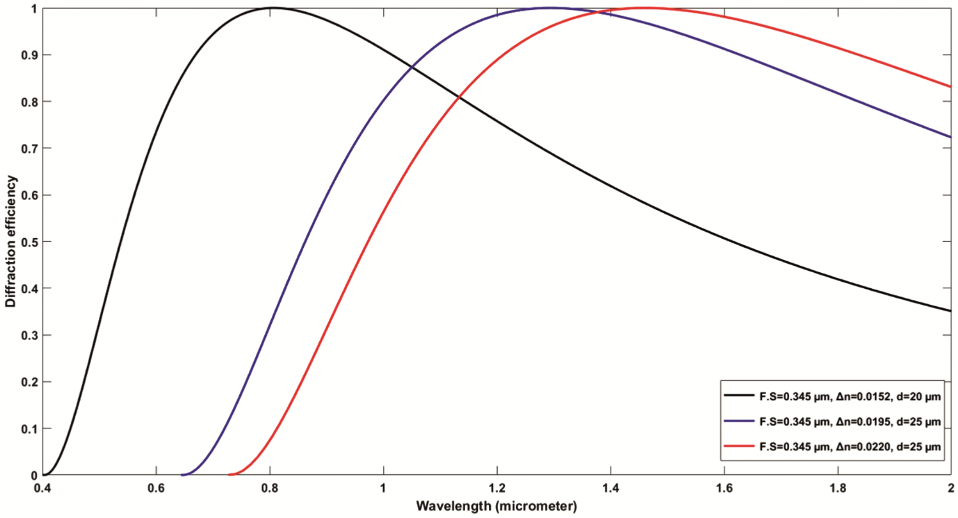

Fig. 5 — Simulation result of (η) vs. (λ) for different (d) and (Δn), with fringe spacing (ʌ = 0.345 μm) constant, at 850 nm, 1310 nm, and 1550 nm

Curves of Fig. 5 are achieved by adjusting the refractive index modulation depth and film thickness while maintaining the fringe spacing constant ($\Lambda = 0.345\ \mu m$). This improvement attempts to maximize the efficiency of holographic optical components at three critical working wavelengths ($850\ nm, 1310\ nm, and\ 1550\ nm$) suitable for use as couplers in optical fiber communications. The processing parameters of a single holographic optical element were fine-tuned ($\Delta n = 0.0265, \Lambda = 1.666\ \mu m$, and $d = 20\ \mu m$) to ensure significant diffraction efficiency across two optical windows (1250-1350 nm and 1500-1600 nm) at operating wavelengths of 1310 nm and 1550 nm, as depicted in Fig. 6.

2 Experimental Methodology for Holographic L-F Coupler

2.1 Configuration for Recording and Playback of Holographic L-F Coupler

To fabricate a holographic lens for laser to fiber coupler, the interference of a spherical wavefront diffracted from a point source with a coherent collimated laser beam from the same source was made to fall on a high-resolution photosensitive film. This interference pattern results in an off-axis zone plate called a point source hologram or a holographic lens. The exposed film underwent normal developing and fixing process[13-14]. For the present study PFG − 01 high-resolution silver halide film, which is

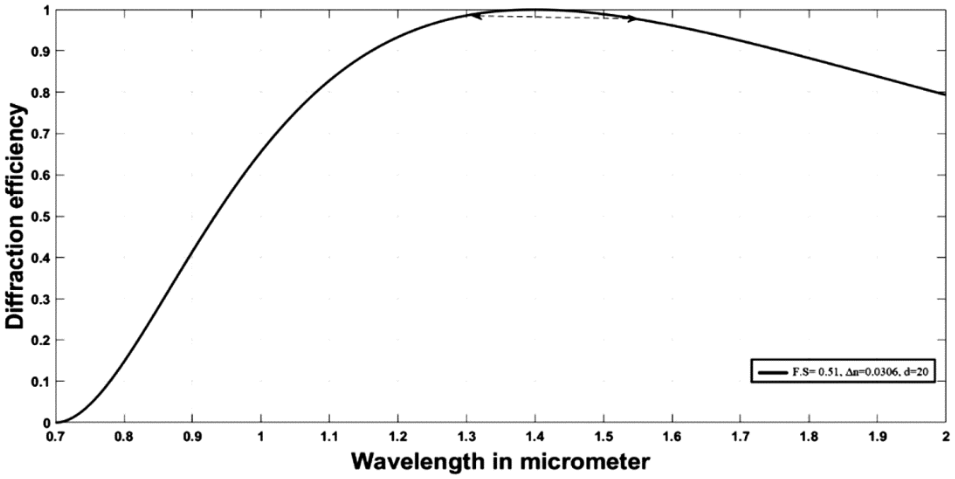

Fig. 6 — Simulation result of (η) vs. (λ) for a LF coupler ($d = 20\ \mu m, \Lambda = 0.51\ \mu m, \Delta n = 0.0306$) at 1310 nm and 1550 nm

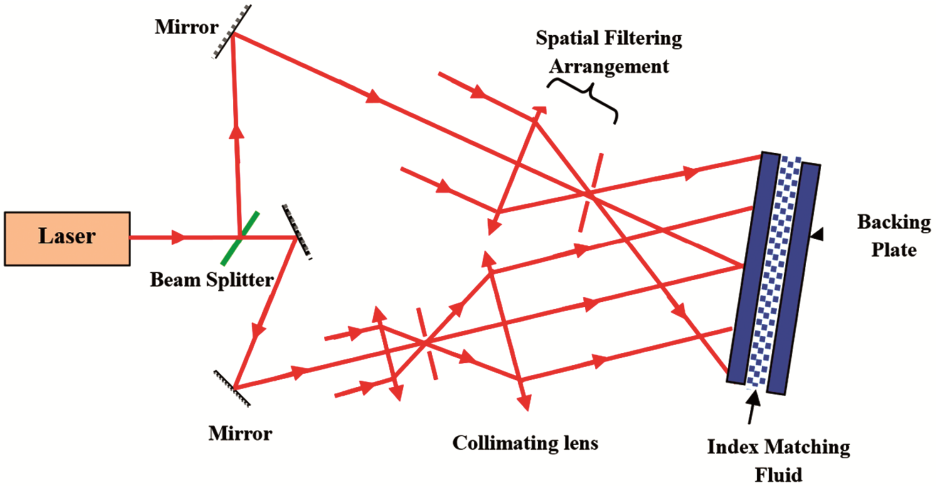

Fig. 7 — Schematic diagram of the setup for recording a holographic L-F coupler

sensitive to $\lambda = 0.6328\ \mu m$ (red wavelength) and has a resolution of 3000 lines/mm with an average grain size of 40 nm was used to record the required holographic lens.

A conventional 10 mW He – Ne laser was used as the coherent light source. The collimated laser beam was sent to a beam splitter, which separated optical source into two equal parts: transmitted and reflected. The reflected optical beam was focused onto a mirror and then passed through a 5 μm-diameter pinhole, creating a spherical wavefront that illuminated the recording film. Simultaneously, the second beam was directed onto the same recording film using reflecting mirrors following expansion and collimation as shown. A spatial filtering configuration was employed for beam divergence and collimation, which included a suitably aligned pinhole to diverge the beam and a converging lens situated at its focal length from the pinhole to generate parallel light rays. The plane and spherical wavefronts illuminated the recording plate simultaneously, resulting in a zone plate that is used to fabricate proposed L-F coupler .

Equal path lengths of transmitted and reflected beams from the beam splitter to the recording plate were maintained to ensure to satisfy the condition of temporal coherence requirement. Figure 7 shows a schematic of the recording geometry, while Fig. 8 (a-b) present photographs of the experimental setup for recording the coupler and the recorded lens, respectively. To maximize efficiency, holographic lenses were recorded at various exposure times.

2.2 Playback Geometry of Recorded LF Coupler

Figure 9 depicts a schematic layout of the experimental setup used to produce a focused beam of light when a holographic LF coupler is illuminated by

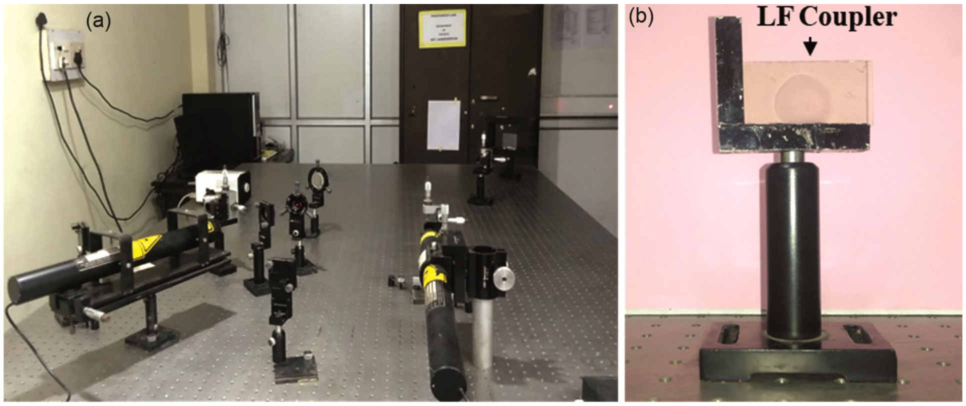

Fig. 8 — Experimental setup of (a) setup for recording a holographic L-F coupler and (b) recorded LF coupler

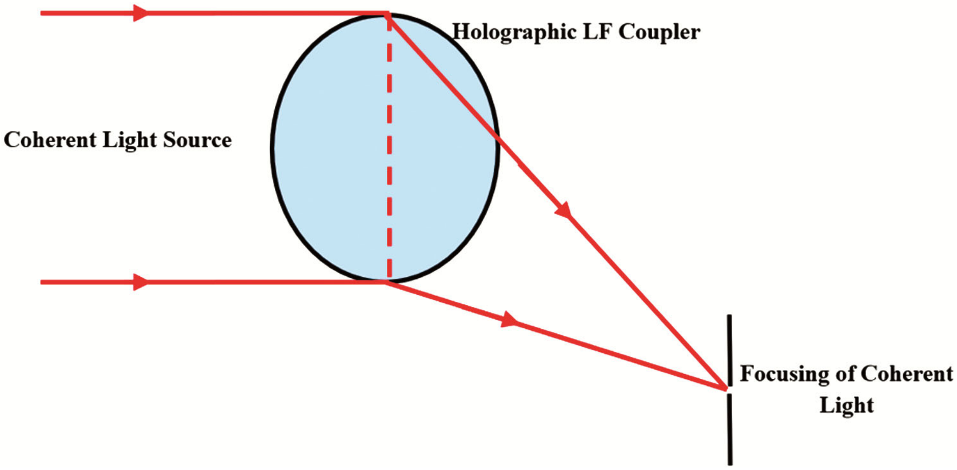

Fig. 9 — Playback layout of the holographic LF coupler under coherent light source illumination

a parallel beam of coherent light. In this proposed system, the plane wavefront illumination of the holographic lens serves as the reconstructing wave, resulting in a converging wavefront. The diffraction efficiency of the recorded LF coupler is investigated at four distinct wavelengths ($\lambda = 633\,nm, 532\,nm, 516\,nm, and\ 488\,nm$), using the setup illustrated in Fig. 9. The recorded lens has a film thickness of $7\,\mu m\,(PFG-01)$, a fringe width of $0.59\,\mu m$, and a refractive index modulation depth of $\Delta n = 0.0159$. The experimental diffraction efficiency curve closely resembles the theoretical curve for the identical parameters, as illustrated in Fig. 10. The coupler performance is accurate and consistent across multiple data sets. The accuracy of the holographic recording method and its suitability for a range of wavelengths are highlighted by this thorough experimental and theoretical comparison.

Figure 11 (a) shows a photograph of the experimental setup used to produce a focused point with the LF coupler. A $10\,\mu m$ pinhole in a spatial filter configuration creates a spherical wavefront illuminated by the first holographic lens (HL_1). This interaction creates a planar wavefront, which then illuminates the second holographic lens (HL_2), resulting in a converging spherical wavefront that focuses on the core of the optical fiber. The laser diameter of the focus point was measured by recording the image of spot on a $PFG-01$ plate. The plate was then developed and stabilized according to conventional procedures. Figure 11(b) shows a photograph of the resulting focus point. The diameter of the recorded focused point was measured using a microscope with a resolution of $10\,\mu m$, providing an approximate value of $300 \pm 10\,\mu m$.

The experimental setup and proposed system design considerations in this study demonstrate that HOEs can outperform traditional optical systems, notably in OFC. This research advances our understanding and application of LF couplers,

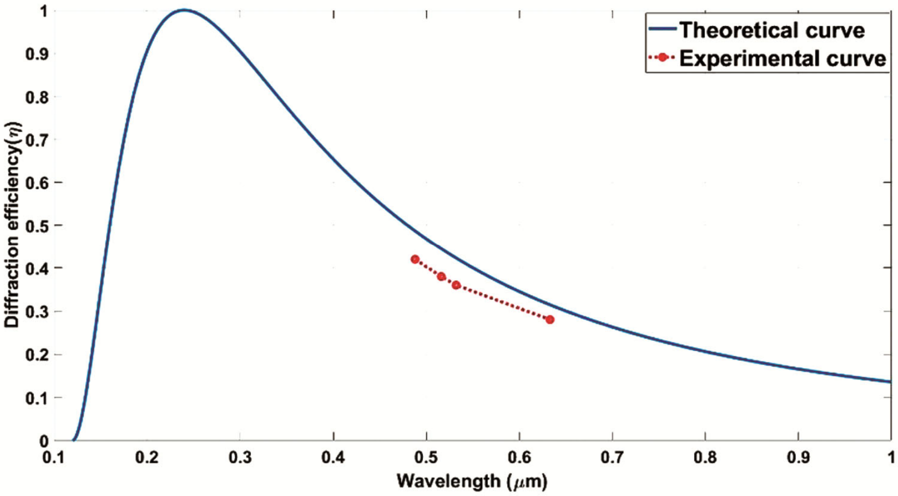

Fig 10 — Experimental and theoretical comparison of (η) vs. (λ) for a LF couplers with optimizing parameters $d = 7\ \mu m, \Lambda = 0.59\ \mu m$, and $\Delta n = 0.0159$

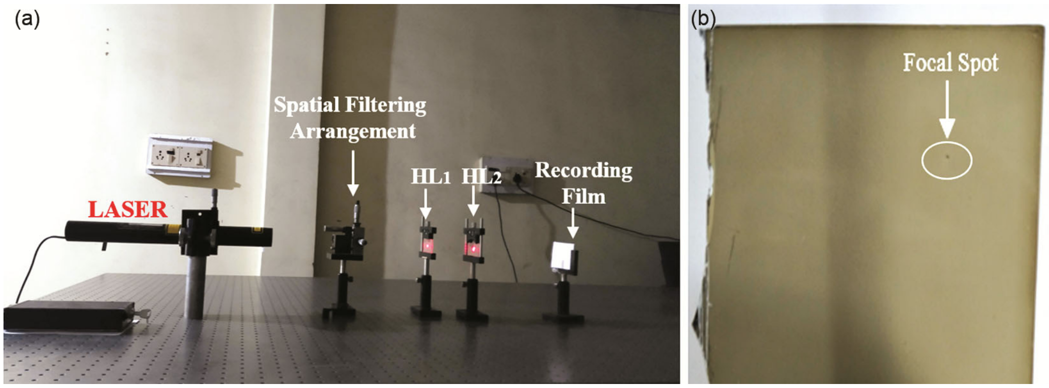

Fig. 11 — (a) Experimental setup utilized to record a laser beam spot size of a focused point using the LF coupler, and (b) shows an image of the holographically recorded spot size $(300 \pm 10)\mu m$ of laser beam incident to the core of optical fiber

opening the path for future advances in optical communication technologies. The measured spot size $(300 \pm 10)\mu m$ of the coupled optical signal shows that LF coupling is possible with proper design considerations and an advanced laboratory setup.

3 Conclusion

This work presents the necessity and methodology for optimizing essential parameters such as film thickness (d), index modulation depth (Δn), and fringe spacing (Λ) to enhance the coupling efficiency of laser-to-fiber holographic coupler recorded in (PFG − 01) silver halide media. We used a coupled wave theory-based approach to perform a detailed theoretical investigation of the impact of these parameters on η at different wavelengths. The adjusted parameters used to design the proposed LF coupler with excellent efficiency in two optical transmission windows of $1250 - 1350$ nm and $1500 - 1600$ nm, which correspond to operating λ of 1310 nm and 1550 nm, respectively. Our findings show that only one coupler may be used efficiently inside these optical windows, providing great flexibility and performance. The experimental setting and design considerations of this work demonstrate that HOEs can outperform in comparison to conventional optical systems, especially in optical fiber communications. This study advances the understanding and implementation of LF couplers, as well as sets the stages for future developments in optical communication technology. Furthermore, the practicality and cost feasibility of these holographic lenses can be improved by large-scale manufacturing through replication. As a result, improved LF holographic couplers appear to be a potential approach for designing efficient, high-quality optical communication systems.

Reference

1 Gabor D, *Nature*, 161 (1948) 777.
2 Saxby G, *Prentice Hall International UK*, 1985, 106.
3 Hariharan P, Basics of holography, *Cambridge University Press*, 2002.
4 Schwar M, Pandya T & Weinberg F, *Nature*, 215 (1967) 239, doi: 10.1038/215239a0.
5 Singh A K *et al.*, *Optik*, 261 (2022) 169184, doi: 10.1016/j.ijleo.2022.169184.
6 Kogelnik H, *The Bell System Technical Journa*l, 48 (9) (1969) 2909, doi: 10.1002/j.1538-7305.1969.tb01198.x.
7 Pappu S V, *Optics & Laser Technology*, (1989) 305.
8 Pappu S V, *Optics & Laser Technology*, (1989) 365.
9 Bergman L A *et al.*, *Opt Engg*, 25 (1986) 1109.
10 H. Yamashita *et al.*, *Japanese J Appl Physi*, 2019, doi: 10.7567/1347-4065/ab2534.
11 Hogari K, Yamada Y & Toge K, *J Lightw Technol*, 26 (17) (2008) 3104, doi: 10.1109/JLT.2008.926931.
12 Charbonneau-Lefort M & Yadlowsky M J, *J Light w Technology*, 33 (4) (2015) 872, doi: 10.1109/JLT.2015.2390223.
13 Soares O D D, *Opt Engg*, (1981) 740, doi: 10.1117/12.7972800.
14 Chang B J & Leonard C D, *Appl Opt,* 18 (1979) 2407.
15 Shakher C & Yadav H L, *J Opt (Paris)*, 21 (1990) 267.
16 Chakraborty D *et al.*, *Photonics*, 9 (12) (2022) 936.
17 Chakraborty D *et al.*, *Br. and Irish Conf. on Optics and Photonics*, pp. Th3A-2, Dec. 2024.
18 Khonina S N, Kazanskiy N L & Butt M A, *Laser & Photonics Rev*, 18 (12) (2024) 2400377.
19 Ghosh A & Nirala A K, *Meas Sci Technol*, 28 (12) (2017) 125402.
20 Ishii Y & Kubota T, *Appl Opt*, 32 (23) (1993) 4415.
21 Yoshino T, Kubota T & Ose T, *Appl Opt*, 22 (12) (1983) 1800.
22 Sankar S P, Hariharan N & Varatharajan R, *Wireless Pers Commun*, 87 (2) (2016) 419.
23 Edwards C A, Presby H M & Dragone C, *J Lightw Technol*, 11 (2) (2002) 252.