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Trends in micro-optics and nanophotonics technology

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This article is dedicated to Prof Kehar Singh for his significant contributions to Optics and Photonics

Micro-optics and nanophotonics cover areas of refractive and diffractive micro-optics, metamaterials, photonic crystals, and silicon photonics. Processes have been developed for the fabrication of micro-optical elements like microlens arrays, computer generated holograms and diffractive lenses. Applications based on micro-optics like compact and lightweight cameras, wavefront sensors, and aspheric optics testing using diffractive null elements are being targeted. In collaboration with various leading academic research groups in the country, futuristic applications that use nanostructures based on metamaterials, photonic crystals and silicon photonics are being identified. This paper will cover major initiatives taken by IRDE (India) in the area of micro-optics and nanophotonics technologies and their defense applications.

Keywords: Micro-optics, Nano photonics, Metamaterials, Photonic crystals

1 Introduction

The last few decades have seen the optics industry adopting some of the fabrication techniques used in semiconductor industry. This has paved the way for two major trends in optics industry – miniaturization and large volume production. Miniaturization has resulted in reduction of system volume thereby reducing system weight. Cost effective techniques for large volume production have resulted in low cost devices. Micro-optical components are increasingly finding many diverse applications.

In the field of nanophotonics the motivation is to control the optical properties of materials. Nanophotonics is defined as the science and engineering of light & matter interactions that take place on wavelength and sub-wavelength scales where the physical, chemical or structural nature of artificial nanostructured matter controls the interactions. An enormous range of technological developments would become possible if we could engineer materials that can provide us complete control of light propagation over the desired range of frequencies.

Keeping in view the futuristic applications offered by these emerging technologies, DRDO has taken an initiative in 2012 in collaboration with leading R&D institutions of India, to develop and harness them. The main technologies developed in micro-optics and nanophotonics areas and their useful applications are discussed in this paper.

2 Micro-optics

IRDE, Dehradun, India has developed micro-optical components such as microlens arrays and computer generated holograms for various applications including wavefront sensors, imaging, null testing of aspheric optics and pattern projection.

Microlens arrays are arrays of small lenses (less than 2-3 mm) which find useful applications in minimizing the size and weight of an imaging system, increasing the effective fill factor of a light sensor,

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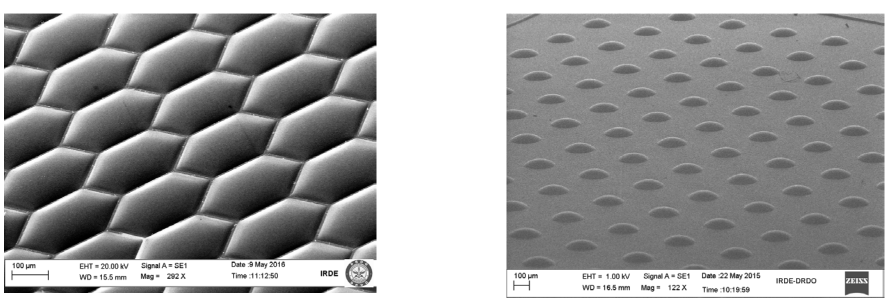
sensing the local slope of an incoming wavefront, shaping the output of a laser beam and in optical interconnection etc. [1,2]. Fabrication of microlens arrays has been a challenging task and many different fabrication techniques, such as thermal reflow [3,4], ultraviolet curing of polymer [5], micro-jet printing [6], LIGA (Lithographie, Galvanoformung, Abformung), and hydrophobic effect [8] have been proposed in the literature. However, thermal reflow technique is mostly used for microlens array fabrication as a wide range of parameters can be realized by this technique. In this technique, standard photolithographic process is used to create photoresist pillars of desired dimension [3] on a substrate. These pillars are then reflowed (melted) at an optimized temperature and time, such that the surface tension pulls these pillars into the shape of spherical lens [9].

We have realized microlens arrays with diameters ranging from 200 µm to 1 mm, sag varying from 3 µm to 60 µm with circular, square or hexagonal apertures [10,11]. For realizing small F# lenses (< 5), we use two methods, (1) thermal reflow on thick photoresist and (2) molding method where we use moulds fabricated by single point diamond turning machine. For large F# lenses (>10), we mainly use thermal reflow in controlled environment to obtain the spherical lens profile. Arrays with 30 × 30 microlenses and fill factor upto 95% have been realized and their use in wavefront sensing has been demonstrated. Figure 1(a) shows the scanning electron microscope (SEM) image of a microlens array with hexagonal aperture. These microlens arrays are replicated by soft lithography technique [12] in order to transfer the lens profile from photoresist to a stable polymer. Figure 1(b) shows the SEM image of microlens array with circular aperture and high sag (~50 µm). Some experiments on fabrication of infra-red microlens arrays on silicon have been performed where dry etching is used to transfer profile of lenses onto the underlying silicon substrate.

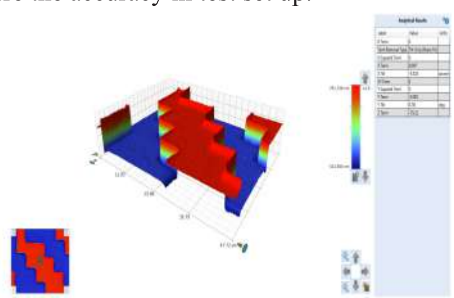
Computer Generated Holograms (CGHs) are diffractive optical elements (DOEs) that can manipulate the incident light almost arbitrarily [13]. In contrast to conventional recording of holograms, which requires a physically existing object to record the fringe patterns, CGHs are calculated on a computer. They find wide applications in two-and three-dimensional image displays, laser beam shaping, interferometry, and optical data processing [13,14]. CGHs are basically typical numeric-type digital elements with random like structures and are sampled in the x and y directions over discrete cells or pixels which can take on any amplitude or phase values. These are fabricated as either transparent and non-transparent patterns (in case of amplitude CGH) or variations in etch depth (in case of phase CGH) both of which diffracts the light that is incident on them. The phase levels of the CGHs are constrained or quantized over the levels that can actually be fabricated with the available fabrication tools (e.g. 2, 4 or 8 levels). However, a binary phase CGH is easier to fabricate than one consisting of multiple phase levels. IRDE has obtained expertise in design, fabrication and characterization of a binary phase as well as amplitude CGH for various applications. Depending upon the applications, various design methodologies have been developed.



(a) (b)

Fig 1. (a) shows the SEM image of micro-lens array with high fill factor and hexagonal aperture. (b) shows the SEM image of micro-lens array with high sag and circular aperture.

The design of CGH was done using ray tracing calculations by computing the optical path difference (OPD) of rays originating normal to aspheric surface to the CGH plane and the OPD of the rays traced from a reference surface. We have formulated a simple method to design CGH based on purely geometrical approach using MATLAB code. The resulting phase is encoded in the computer generated hologram. The required tilt is added to this phase to isolate the desired order (–1 order) in the Fourier plane of CGH. We have used a spherical beam, and sampling requirements are thus reduced resulting in reduction of the computation time. Another important factor is that due to low spatial frequency, the minimum feature size is not very small and the fabrication process is easier and errors are sufficiently reduced. An aspheric surface generated on germanium with clear aperture of 64 mm at IRDE, Dehradun (India) was tested using the CGH. The CGH designed using above procedure is fabricated by maskless lithography technique to make an amplitude (chrome on glass) hologram. The substrate used for the fabrication is BK7 plate with transmitted wavefront error better than 0.1 wave to ensure the accuracy in test set up.



(a) (b)

Fig 2. (a) shows the profile of a CGH using non-contact profiler. (b) shows the 3-D image of (a) as taken by non-contact profiler.

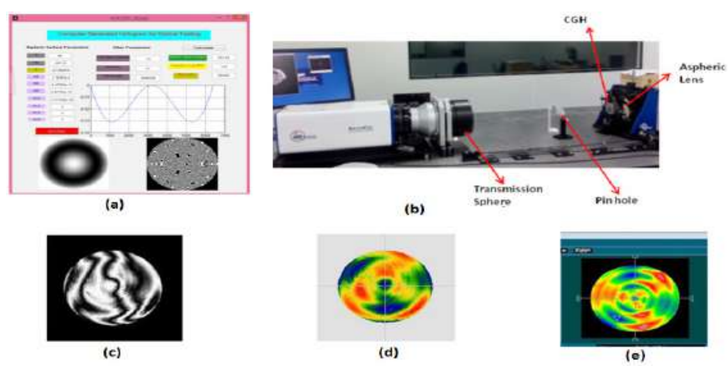


Fig 3. (a) GUI for CGH design software for 64mm optics (b)Test set up for testing aspheric using CGH (c) The interferogram (d) The phase map of the aspheric surface measured using CGH (PV = 521nm) and (e) Phase map of the aspheric using ZYGO verifire asphere interferometer (PV = 518nm).

For diffractive null design, ray trace method has been used, while for projection of a pattern, CGH is designed by Iterative Fourier (or Fresnel) Transform Algorithms [15]. The designed binary CGH is realized by lithography process. A chrome coated glass substrate is patterned by UV-photolithography process using a maskless lithography system [16,17]. For phase CGH, the substrate was etched precisely by dry etching process. It is possible to replicate the micro-structures to a stable polymer by soft lithography technique [12]. For characterization, 3-D non-contact optical profiler and scanning electron microscope have been extensively used. Figure 2 (a and b) show the profile of a CGH using optical profiler. CGHs with feature sizes as small as 5µm and pattern size as large as 40 mm × 40 mm have been achieved [16-18], and the technology has been established at IRDE for testing of aspheric optics using CGH as null element.

The CGH is used to test the aspheric surface generated on germanium on a commercial Fizeau interferometer. The verification of the process is done by experiment and comparison with the measurement performed by Aspheric Interferometer, which is a standard instrument for measuring aspheric surfaces. The were obtained from CGH test (PV = 521nm) and aspheric interferometer (PV = 518nm) are in close agreement as shown in Fig 3.

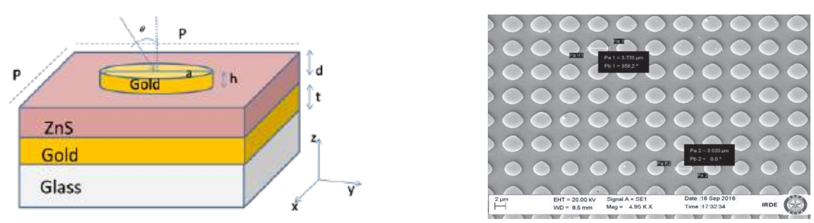
3 Nanophotonics

IRDE, Dehradun, has been actively working on metamaterials and photonic crystals in collaboration with IIT Kanpur, IIT Delhi and IISc Bangalore and on silicon photonics in collaboration with IIT, Madras, India.

(*a*) *Metamaterials*

Metamaterials are artificially engineered nanostructures of dimensions much less than the wavelength of light. Metamaterials have immense defence applications such as electromagnetic invisibility, broadband high efficiency absorbers, frequency selective absorbers etc.

A very good expertise has been developed for design, simulation, fabrication, and characterization of highly absorbing metamaterials at various frequencies ranging from visible to NIR to LWIR to Radar frequencies. A typical unit cell design of metamaterial absorber is shown in Fig 4(a) and SEM micrograph of fabricated metamaterial for a LWIR frequency is shown in Fig 4(b). Metamaterials perfect absorbers have been successfully demonstrated with absorption as high as 95% experimentally. Indium Tin Oxide (ITO) based broadband metamaterial absorbers with transparency in visible spectrum has been shown and also flexible metamaterials have been reported. For switchable metamaterials vanadium oxide (VO_2) ground plane has been used [19-22].



(a) (b)

Fig 4. (a) A typical unit cell design of a metamaterial absorber consisting of metal-dielectric-metal trilayer with patterned top metal layer. (b) SEM image of a fabricated absorbing metamaterial for LWIR frequencies.

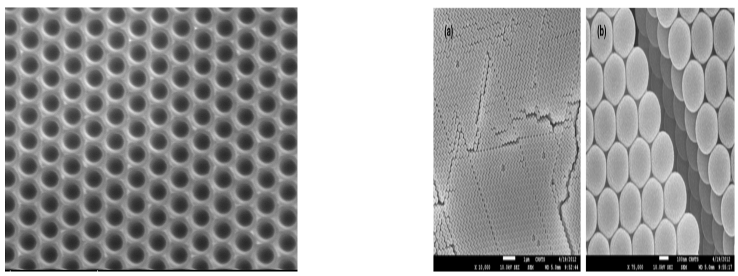
In collaboration with IIT Kanpur, the possibilities of using highly absorbing metamaterials on a micro bolometer to enhance the efficiency of present infra-red detectors are being explored.

Infra-red absorbers can also be used to modify the emissivity of any object by tuning the black body radiation. This can find major applications in thermal camouflaging.

(*b*) *Photonic crystals*

The research in photonic crystals opens new possibilities for an "optical chip" – leading to strong hopes for large-scale integration of optoelectronic components. The research area enables the design and implementation of wavelength-dependent and wavelength independent optical devices that are ultra-small in size, compact, tunable and versatile for applications. Additionally, polarization properties can be in-built during the design stage and the device characteristics can be either active or passive. A very good expertise has been obtained in design, simulations, fabrication and characterization of 2-D and 3D photonic crystals structures.

For 2-D photonic crystal fabrication, focused ion beam (FIB) system has been used. Figure 5(a) shows a photonic structures made on silicon wafer with precisely controllable hole size. The capabilities for designing a photonic crystals based, compact on-chip lasers with ultra-low thresholds have been demonstrated [23,24]. Apart from this self-assembled photonic crystals (3-D PhC) have been fabricated from colloids by horizontal self-assembly and characterized for their photonic stop band characteristics. A typical 3-D photonic crystal structure is shown in Fig 5(b). A Photonic crystal patterned energy efficient detection system has been demonstrated [25] in IIT Kanpur, India. The enhancement in efficiency is due to reduced Fresnel reflection from the surface of a solar cell.



(a) (b)

Fig 5. (a) A typical 2-D photonic crystal structure in silicon made by focussed ion beam milling; approximate hole diameter is 365 nm and hole separation is 600 nm. (b) 3-D photonic crystal structure made by colloidal self-assembly method; approximate colloid size is 235 nm.

A miniaturized photonic band-gap resonator based device has been realized at IISc Bangalore (India) for sensing the mechanical force. The technology of design and fabrication of photonic crystal ring resonator on a silicon cantilever has been established. The minute change in resonant wavelength shift during deformation of the cantilever due to external force is sensed in this device.

(*c*) *Silicon Photonics*

Silicon photonics is an ideal platform for optics and electronics integration and it is supposed to play a key role in realizing data communication at lightning speed. In collaboration with IIT Madras, India, technologies are being developed for design and fabrication of various silicon photonics components. The main highlights are given below [26-34].

- The single mode waveguide in silicon on insulator (SOI) substrate with varying device layer thickness (5 µm – 250 nm) has been demonstrated. The propagation loss for large cross-section rib to small cross-section photonic wire waveguides varies from 0.5 to 2.0 dB/cm.
- A novel adiabatic spot-size converter has been demonstrated to integrate micrometer to sub-micrometer waveguides to enable large-scale on- chip integration. The measured insertion loss of such a typical spot-size converter is ~ 0.5 dB.
- A dispersion-free inter leaver design has been proposed, fabricated, and characterized. It is designed to separate alternate DWDM channels with 100 GHz spacings.
- A metal coated rib waveguide structure is shown to improve the polarization extinction of integrated optical device fabricated in SOI platform.
- A micro-ring resonator has been designed and fabricated as shown in Fig 6.

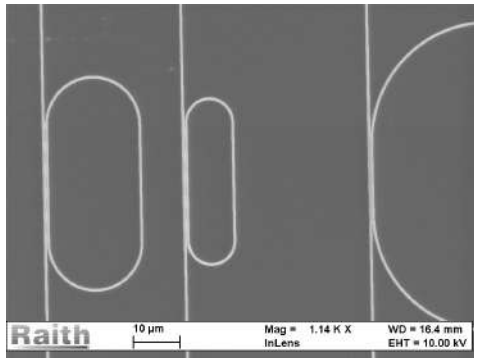


Fig 6. SEM image of a micro-ring resonator using photonic wire waveguides, fabricated by e-beam lithography at IIT – Madras.

4 Conclusions

There is clearly a potential for micro-optics and nanophotonics to have a significant impact on military systems. Although, micro-optics is relatively mature but nanophotonics research is in earlier stages relative to other technologies, and applications may require a lot of investments and time before they are realized. Moreover, the applications of nanophotonics require support from other enabling technologies. Applications of micro-optics and nanophotonics will change the current state of military technology. There is a high probability that the technologies emerging from the realm of micro-optics and nanophotonics, particularly in the area of metamaterials and plasmonics, could potentially enable much more compact and efficient devices than is currently available.

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He has published around 50 papers in different National, International journals and processed for three patents in the area of optics, optical coatings and photonics.

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