Photonics Technologies for Advanced Electro-Optic Sensors

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1. INTRODUCTION

This decade has been witnessing a rapid growth in photonics research and technologies owing to large number of applications in civilian as well as in defence. The major applications of photonics technology in defence include sensing, surveillance, target detection & acquisition, command control, communication & intelligence, guidance & navigation and electro-optic countermeasures.

This presentation overviews the recent developments being pursued in the area of optical image processing, integrated optics, adaptive optics for high resolution imaging and holography at IRDE. All these advanced technologies are helpful in enhancing the capabilities for Electro-optical system for defence application.

Integrated optics (IO) is miniature optics capable of performing various operations such as generation, modulation, switching, multiplexing, filtering, processing etc. of optical signals. The advantages offered by them, *vis a vis*, bulk optical systems are in terms of reliability, lower cost, lower power consumption and higher speed. They are also compact and light weight. Such circuits are being used in the area of telecommunications for high speed signal encoding, high speed switching, multiplexing/de-multiplexing of optical signals, they are also expected to be optimum devices in sensor signal processing, spectrum analysis, logic operations and computing. The paper discusses the salient features of integrated optic chip for fiber optic gyro and periodic poled lithium niobate chips for tunable lasers in 2-5 μm developed at IRDL.

Holography, a technology for three dimensional imaging has also finding many uses in electro-optical system with the advancements in solid state devices, recording media and compact laser sources. It is widely used in non-destructive testing, display, high resolution imaging. As a holographic optical element which are light weight find applications in Holosight, optical communication etc. Results of Holosight developed at IRDE will be presented.

Optical correlators can be effectively used for automatic target recognition, missile guidance and tracking of the target which do not have prominent features or high content with the background. Inherent parallel capability of optical processing enables to simultaneously recognise and locate all objects in the scene almost instantaneously.

Adaptive optic systems are used to improve online image quality by reducing phase aberrations introduced due to atmospheric turbulence. An adaptive optic image system has been developed for 50 km range. A critical analysis of various subsystems viz imaging telescope, fast wavefront sensors, tip-tilt mirror, and deformable mirror will be presented.

2. INTEGRATED OPTICAL DEVICES

IRDE has created infrastructure to fabricate IO devices and developed various devices like 3dB splitter, directional coupler, 1 x 8 splitter, etc. commonly used in Fiber Optics Communication. We shall here present salient features of IO chip and periodic poled lithium niobate (PPLN) devices.

2.1 Integrated Optic Chip for Fiber-Optic Gyros

The fiber-optic gyroscope is today an important instrument for many civilian and military applications such as inertial navigation and guidance systems for automotive, aircraft, and space industries; satellite antennas pointing and tracking; mining and tunneling operations; helicopter attitude control, etc. It brings the advantages of solid-state technology (guided-wave optics and low-voltage low-power electronics) with a cost reduction that enlarges the application domain. FOG consists of a large coil of optical fibre and uses the interference of light to measure angular velocity. For the measurement of rotation two light beams are coupled into the coil in opposite directions. If the sensor is undergoing a rotation then the beam traveling in the direction of rotation will experience a longer path to the other end of the fibre than the beam traveling against the rotation, as shown in Fig. 1. This is known as the Sagnac effect. When the beams exit the fibre they are combined. The phase shift introduced due to the Sagnac effect causes the beams to interfere, resulting in a combined beam whose intensity depends on the angular velocity. It is therefore possible to measure the angular velocity by measuring the intensity of the combined beam. The dashed line is the path taken by the beam traveling in the direction of rotation. The solid line is the beam traveling against the rotation. è is the angle through which the gyro turns whilst the beams are
in flight. Several critical system components and design characteristics affect the FOG performance: the coil optical fiber; the active source; the passive and integrated-optics components; the optical circuit configuration for reciprocity; and the detection schemes. Unlike mechanical gyroscopes, optical gyroscopes contain no moving parts and require only a few seconds to start-up.

IRDE has recently designed and fabricated a Multi-Component Integrated Optic Chip (MIOC) for fiber optic gyroscope. MIOC consists of a polarizer, 3-dB splitter and phase modulator as shown in Fig 2. Proton exchange (PE) process based IOC is an approach, which support only one polarization mode of waveguide i.e., entire PE circuit itself work as a polarizer. The polarizing properties of PE waveguide are broadband and extinction ratio can be achieved up to 60 dB. Direction of propagation has been chosen in Y direction to make use of the maximum electro optic coefficient ($r_{33}$) of the LiNbO$_3$. The MIOC starts with an input channel waveguide followed by a splitter with waveguide width such that it support single mode at 1550 nm. Electrode length of the phase modulator has been designed and fabricated for $V_p$ voltage to be less than 4.0 volt.

The output separation of the two arms of the MIOC is 250 mm which is compatible for fibre pig-tailing with commercially available V-grooves. Fig. 3 shows the packaged device with fiber at input and output end.

2.2 Non linear Integrated Oplca Devices

2.2.1 PPLN Chips

In recent years, periodically poled ferroelectric materials have gained significant importance in nonlinear frequency conversion processes. These find tremendous application in the generation of Optical Parametric oscillators (OPO), Bragg Reflectors, Second Harmonic Generators (SHG), and photonic bandgap devices. Electric field poling technique has been widely used to achieve the required periodically reversed domain structure in Lithium Niobate (LN) wafers.

IRDE has taken up a project on the design and development of Periodically Poled LN (PPLN) chips for the nonlinear frequency conversion applications. This work includes establishment of state-of-the-art PPLN fabrication facility, optimization of E-field poling parameters for inverting the domain structure of LN and characterization for fabricated PPLN chips for their utility in nonlinear frequency conversion. In this project it was proposed to fabricate PPLN chips for Second Harmonic Generation (SHG) of green wavelength and 2-5 μm tunable output using 1064 nm Nd:YVO$_4$ laser as a pump source. As per our design calculations for SHG green domain periodicity comes out to be 6.5 μm whereas that for 2-5 μm tunable output, periodicity ranges between 25.5 μm to 31.5 μm.

PPLN chips have been fabricated at IRDE for the first time in the country. Recently Fanned and Multi grating PPLN chip are been fabricated for generating tunable output (2-5 μm) using E-field poling technique. In fanned grating period continuously varies from 25.5 μm to 31.5 μm whereas in multi-grating PPLN chip it varies in steps of 0.25 μm.
We have used standard optical grade LiNbO₃ wafer of congruent composition with the arrangement Z-cut, 0.5mm thick LN wafers were spin-coated with a thick positive photosist layer followed by photolithography using a Mask Aligner to pattern the periodic electrodes. In this way a thick layer of photosist is as applied over the wafer, leaving a portion of the wafer exposed. Contact is made to the exposed LN wafer with LiCl liquid electrolyte. PPLN fabrication is achieved at room temperature by the electric field poling process. A positive voltage pulse slightly exceeding the coercive field of LN (<“21kV/mm) is applied on the z+ patterned crystal face by using a LiCl liquid electrolyte.

The liquid electrode configuration has two electrolyte containing chambers which squeeze the sample between two O-rings, Fig. 5. The polling jig has been specially designed and fabricated for E-field poling application Fig. 5.

**Figure 4. Fanned grating PPLN chip.**

**Figure 5. Electrode configuration.**

In our poling experiments, we have used conventional poling waveform and we have programmed this arbitrary waveform using SRS function generator. First the applied voltage is ramped linearly to a value less than its coercive field value and then it is clamped at a field higher than its coercive field value. When the electric field reaches or exceeds the coercive field, domain inversion starts. Due to charge redistribution within the crystal structure a poling current is generated and from this current information about the temporal dynamics of the poling process is obtained. The poling current drops to zero when the whole connected area has been poled. This sudden drop can be attributed as the end of poling, and the applied voltage V at this specific time yields the coercive field. After poling we clamp the field at a value lesser than its coercive filed for domain stabilization and then we decrease the field to zero by ramping it down linearly. Both current and voltage waveforms are visualized on a four channel oscilloscope during the poling process. The parameters of the domain structure are controlled by the pulse shape and current value.

### 2.2.1. Applications of PPLN

- Second Harmonic Generation (SHG) with high efficiency
  - Blue-Green laser sources for submarine applications
  - Low power dazzlers: Green during day & Blue during night
- Optical Parametric Oscillators (OPO’s)
  - Tunable 2-5 mm PPLN-based OPO’s for IRCM
  - PPLN-based OPO’s are used as sources for LIDAR
  - Optical data storage

### 2.2.2. PPLN-based 2-5 μm Optical Parametric Oscillator

An optical parametric oscillator (OPO) is a nonlinear frequency conversion device in which a pump photon of frequency \(ω_p\) is annihilated to generate a signal photon of frequency \(ω_s\) and an idler photon of frequency \(ω_i\) inside an optical cavity. These three frequencies satisfy the criteria of energy conservation i.e. \(ω_p = ω_s + ω_i\). The cavity contains a nonlinear medium with second order nonlinear susceptibility and the mirror reflectivities are chosen in such a way that either one or both of the signal and idler waves are resonated inside the cavity. When only one of the signal or idler is resonated it is called as singly resonant OPO (SRO) and if both signal and idler waves are resonated it termed as doubly resonant OPO (DRO). An OPO, in some ways, is equivalent to a laser. The parametric gain from the nonlinear process must exceed the total losses in the cavity for any field to build up inside the resonator and for the OPO to be able to deliver signal and idler power. Once this threshold is approached the pump will efficiently convert into the signal and idler waves. OPO find a number of applications in IR countermeasures, sensing of chemical and biological detection, eye safe wavelength generation, NIR spectroscopy, MID-IR spectroscopy, LIDAR, range finding, optical coherence tomography etc.
For efficient frequency conversion an important criteria is that of photon momentum conservation, i.e., $\Delta k = 2\pi \left( \frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_i}{\lambda_i} \right) = 0$ which is not possible due to the dispersion in the medium. Hence, two techniques known as birefringent phase matching (BPM) in which birefringence of the material is exploited to satisfy the phase matching and quasi phase matching (QPM) which is based on periodically reversing the nonlinear coefficient of the material. In QPM, the accumulated phase mismatch is offset by modulating the second order nonlinear coefficient ($d_{33}$) with a period twice the coherence length. In the case of QPM, the energy conservation and phase matching condition can be written as

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \quad (1)$$

$$\Delta k = 2\pi \left( \frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_i}{\lambda_i} - \frac{1}{\xi} \right) = 0 \quad (2)$$

where $\lambda_p$, $\lambda_s$, and $\lambda_i$ are the pump, signal, and idler wavelengths. $n_p$, $n_s$, and $n_i$ are extraordinary refractive indices at pump, signal, and idler wavelengths. $\xi$ is the QPM period or domain grating period. It can be seen from these equations that any wavelength within the transparency range (0.35-5.0 $\mu$m for LiNbO$_3$) of the material can be generated by tailoring the grating period for a particular pump wavelength.

In the case of 2-5 $\mu$m tunable OPO, a fanned out PPLN grating of varying periodicity $\xi$ from 25.5 to 31.5 $\mu$m has to be used inside the OPO cavity for 1064 nm pump source. Fig. 1 depicts the schematic of PPLN based 2-5 $\mu$m tunable OPO. It can be seen by solving equations 1 & 2 that when the crystal is translated across the breadth of the pump beam experiences the different periods at different time intervals generating signal in the range of 1.3 to 1.9 $\mu$m and idler in the range of 2 to 5 $\mu$m as shown in Fig. 7.

In this case, only signal is resonated simply due to the fact that it has lower wavelength band (0.5 $\mu$m) as compared to the idler. Due to this reason OPO mirror coatings become comparatively easy. Hence, we have used cavity mirrors having broadband coatings with reflectivities appropriate for resonating signal wave.

3. HOLOGRAPHY

Holography is the three-dimensional imaging technology. It is a process of recording the image of an object using the special properties of light from a laser. Unlike photography that only records the brightness and contrast of an object, a hologram records brightness, contrast and dimension (amplitude and phase). This technique allows holography to accurately display an object in true three-dimensional fidelity.

The first hologram was conceived and produced in 1948 by Dr. Dennis Gabor, a researcher at the Imperial College of London. For this he received the Nobel prize in physics in 1971. Gabor’s early holograms were created without the use of a laser. Gabor used carefully filtered light for his experiments. The “depth” of his holograms was limited to the thickness of a postage stamp.

Holography is a two-step process. In the first step, hologram is generated by the recording (or computing) of interference between an object and the reference wave. The object wave contains the useful information (data). Thus hologram contains the data in a hidden form, which can be reconstructed in the second step of reconstruction with the appropriate reference wave.

3.1 Holographic Optical Elements

Many of the optical devices for complex applications require a large number of conventional optical elements. Most of these elements serve only one purpose at a time because of their size and shape. For example, a plane glass plate acts as a transparent medium without any lens action and if it is curved (convex or concave) then it acquires a lens action. These conventional elements work on the principle of refraction (or reflection). However, if we make the optical elements by holographic technique, they serve multiple purposes at a time thus making the complete optical device more compact. These Holographic Optical Elements (HOE) work on the principle of diffraction and hence are a subset of Diffraction Optical Elements (DOE). HOE can be made to work as grating, lens, and/or mirror. Focal length of a holographic lens is independent of its substrate size and shape. A plane glass plate, on which an off-axis holographic lens is recorded, can replace two conventional elements—one refractive lens and second reflective mirror.
However, HOE is wavelength sensitive and its aberrations are dependent on the change in the reconstruction wavefront. Therefore, its use is limited to special devices, where their wavelength dependency can be utilized effectively.

Recording a holographic optical element is like making a hologram, where there are two beams (say, A & B), which interfere at the recording plate. In the reconstruction (application), this hologram transforms the incoming wavefront A to a different wavefront B. There are two main geometries to record the HOEs as shown in Fig 1. For simplicity only the part immediately before and after HOE is shown. It is obvious that both beams are coming from the same laser with equal path length to maintain the coherence requirement of interference. Transmission type HOEs are made by recording as transmission hologram, where both beams are incident from same side on the recording plane. Similarly reflective HOE is made by recording as reflection hologram, where two beams are incident from opposite sides on the recording plane. It is clear from the figure that first case is an off-axis transmission lens whereas second is a reflective lens. There are many possibilities for different kinds of HOEs. If both incident beams are plane wavefront then a grating with fixed spatial frequency is made. If one is spherical and another is plane then a lens with variable spatial frequency is made. Similarly by manipulating these two beams, various HOEs are made.

There are various holographic recording materials found in the literature. But the commercial availability and suitability to record HOE limits their number into almost three—Photoresist, Dichromated Gelatin (DCG) and Photopolymer. Photoresist is a good recording material for surface relief holograms and DCG and Photopolymer for volume holograms. Silver halide material, because of its easy commercial availability, is also a popular material for research and prototyping.

Therefore, photopolymer is the ideal recording medium. Though their commercial availability is still a crucial issue, most of HOEs for emerging applications are fabricated on Photopolymer.

Besides many civil applications of holographic optics like holographic gratings in DWDM (Dense Wave Degenerate multiplexing) application in communications, there are some defence applications also. Fabrication of Holographic elements and their integration in the devices are crucial in many defence applications like Pilot’s Head up Display (HUD) of fighter aircraft, Helmet mounted display for soldiers (HMD), and Holographic sight for small weapons. HOEs are crucial in these devices mainly because of their compactness and the ability to serve special purpose.

The critical holographic component of HUD and HMD is a ‘holographic combiner’, which utilizes the wavelength dependency and off-axis nature of holographic elements to make a ‘see-through display system’. It is a dual function optical element which simultaneously acts as an optical window and as lens or mirror.

HUD is used in fighter aircraft to provide various flight and weapon aiming data to the pilot while he is viewing outside the aircraft. Helmet mounted display for soldier is a similar application where data, regarding the terrain and/or target scene through the sight on the weapon, is projected onto the eye with a see-through display. This data is conventionally generated on a small cathode ray tube (CRT). Spatial light modulators (SLM) and Organic Light Emitting Diodes (OLED) are also emerging as replacement of CRT in these systems. Though they are not as cost effective as CRT, technological advances are responsible for their usage.

Since the effective light utilization in crucial in holographic combiners, high diffraction efficiency is essential. Otherwise, brightness of input elements, i.e., Phosphors of intensifier tube, CRT, SLM, and OLED, has to be increased to large extent, which is not feasible. Therefore, DCG and photopolymers are the only suitable recording materials for such HOEs. Most of the earlier systems used HOEs made on DCG but now they are being replaced by HOEs on Photopolymers.

3.1.1 Holographic Sight

One of the important defence applications of holographic elements is Holographic sight for small arms, which has the potential for mass-production. The main component of this device is a hologram, which is similar to the holographic combiner. Instead of an image from an input device like CRT, a reticle image is reconstructed in the hologram. Besides, it simultaneously acts as a transparent glass plate for the see-through target scene. Thus, the reticle image is superimposed with the target scene in the holographic element. This element is an off-axis hologram, which is recorded in transmission mode with object being a reticle mask. Virtual image (reticle) in the reconstruction of this hologram with laser diode is used as an aim point for small weapons.

The wavelength shift of the laser diode due to temperature change causes a shift of reticle position. This is due to the dependency of the diffraction angle on the wavelength. This effect is compensated by using holographic grating.
(or lens) in reconstruction. Use of off-axis holographic lens for this purpose has one more additional advantage of providing collimation for the laser diode. Thus a single holographic element serves two purposes at a time — collimation and passive compensation for the temperature change. The optical geometry of reconstruction, Fig. 9, is folded to make a compact holographic sight. Fig 10. It is mounted on the weapon and the reticle position is aligned (zero-in) with the bore of the weapon beforehand. This provision for zero-in is achieved by the desired horizontal and vertical movement of the reference beam in reconstruction, generated by the off-axis holographic lens.

Figure-11 shows the picture of soldiers firing with holographic sight on INSAS Rifle. Salient features of this sight include the control of reticle brightness, auto-shut down, and low battery indicator. It is powered by two 1.5V AAA cells. It has the advantage of shooting with both eyes open along with fast target engagement and improved accuracy as compared to the conventional iron sight. Because of the transparent hologram acting as a see-through window for the target scene, the sight has unit magnification with large field of view (practically unlimited because of both eyes open). A unique advantage of holographic technology in this sight is its ability to function even if the viewing window (reticle-hologram) is partly damaged in the battlefield. This sight is very useful in close-quarter battle (CQB), especially in counter-insurgency (CI) operations. Besides, the holographic sight can also be used for civil applications like archery (sports) and hunting.

3.1.2. Digital Hologram

Recent trend in holography is to record on a Charge Coupled Device (CCD), in this case it is called digital hologram. Digital hologram can be numerically reconstructed on computer. This type of hologram can be stored in a digital database, or can be transmitted through usual communication channels. The useful information content (object) in digital hologram can not be reconstructed without the knowledge of reference wave. Therefore this technique has tremendous applications in the field of information security.

The interference pattern of hologram can also be computed on computer using the virtual scheme of recording. This hologram is called computer generated hologram (CGH). This hologram can be reconstructed optically by using a Spatial Light Modulator (SLM) and appropriated reference wave. It can also be reconstructed digitally, similar to a digital hologram. It is obvious that CGH also has applicability in the field of information security.

Due to the ongoing commercial development of holographic compact disk, and thrust on the information security in this digital era, worldwide research in the holographic coding
techniques has been continuing with a rapid pace. One of the approaches in this area is the use of random phase encoding technique. In this method images or holograms are transformed, by using random phase masks, into noise distributions. This makes the original information hidden for a trespasser. The random phase mask acts as the key to recover the original data from the coded noise distribution by holographic reconstruction algorithm.

4. HYBRID PHOTONIC CORRELATOR FOR AUTOMATIC TARGET RECOGNITION APPLICATIONS

Target recognition plays a key role in automatic target recognition (ATR) and machine vision. Due to the parallel processing capability and high speed of light, optical information processing technologies have found promising applications in ATR from the defense point of view. In real-life situations, the targets are often present with aspect view angle variations and its size (range) also changes as the sensor approaches the target and depression angle variations can also exist. Since correlation forms the basis of any pattern identification process, template matching by optical correlation has proved to be quite efficient and fast. Templates containing features of a known image referred to as correlation filters are matched with an unknown input image to produce sharp correlation peaks if the two images are similar.

There are two well-known optical correlation architectures namely the VanderLugt correlator (VLC) and Joint transform correlator (JTC). In JTC, a complete databank of reference images needs to be priorly stored. The input test pattern and each stored reference are jointly displayed in the input plane of a Fourier transform (FT) lens to get the Joint Power Spectrum (JPS) at the back focal plane of the lens. The captured JPS is then inverse Fourier transformed to achieve correlation. Correlation peaks are produced, only if there is complete matching between the test and the reference pattern. The JTC technique fails if the test pattern undergoes distortions like rotation, scaling, etc. On the other hand, VLC requires the synthesis of a matched filter prior to correlation, which can cater to the real-time distortions. The filter is synthesized with the set of reference images and hence the reference set of images need not be stored. The FT of the test image gets optically convolved with the filter in the Fourier domain. The convolved product is then optically inverse Fourier transformed to obtain the correlation peaks. The alignment in VLC is extremely critical, since there should be a precise pixel-wise matching between the target FT and frequency plane filter.

IRDE has developed a hybrid photonic Correlator for target recognition, which is not only simple but robust in terms of its architecture. Since it utilizes the inherent speed and compactness of optics while harnessing the strength of electronic memory and data handling, it is better referred to as the hybrid photonic correlator. In this, real-time targets captured through CCD/IR camera are correlated at the speed of more than 1000 images per second of size 512x512. For real-time distortion-invariance, the wavelet-modified maximum average correlation height (WaveMACH) filter has been adopted in the hybrid correlator development.

4.1 Description

The schematic for the hybrid photonic correlator is shown in Fig. 12 and the prototype developed at IRDE is shown in Fig. 13. This geometry for correlation combines the advantages offered by both VLC and JTC geometries. In this approach, the input image is digitally Fourier transformed and multiplied with the digitally pre-synthesized distortion-invariant filters to obtain a product function. This product function is displayed on an electrically addressed SLM (CRL Opto SLM from USA), which is illuminated with a coherent collimated beam of laser light ($\lambda = 670$nm). An optical Fourier transform of the displayed product using a lens of $f = 135$mm results in an undesired $dc$ and $\pm 1$ orders corresponding to the two auto-correlation peaks. The resultant peaks are captured on the CMOS camera (from DALSA, USA).

Figure 12. Schematic of hybrid correlator.

Figure 13. Prototype of hybrid correlator developed at IRDE.

4.2 Distortion-invariant Filters

Correlation filters are two-dimensional finite impulse response filters whose output is expected to be stable and predictable in response to a known class of input patterns. Detection of real-time distorted targets is a challenging task in ATR applications. In order to cater to the real-time
distortions like scaling and rotation, several distortion-invariant filters were studied such as the Phase-only filter (POF) & Binary phase-only filter (BPOF), Circular harmonic function (CHF) filter, Logarithmic radial harmonic filter (RHF), Minimum average correlation energy (MACE) filter and the Maximum average correlation height (MACH) filter. The MACH filter has been found to give the best results in the presence of distortions. The Wavelet-modified Maximum Average Correlation Height (WaveMACH) filter has been finally zeroed down, since the use of the Mexican-hat wavelet function with the MACH filter not only enhances the discrimination capability but also increases the correlation peak intensity for the true class image in comparison to the false class image.

4.3 Experimental Results

In hybrid digital–optical correlator architecture, the input scene/target recorded at video rate (25 Hz) is Fourier transformed. A data bank of distortion invariant WaveMACH filters is created. This WaveMACH filter offers good performance in terms of good distortion tolerance and the ability to suppress clutter noise. A total of 25 filters (seven filters for in-plane rotation invariance, 12 filters for out-of-plane rotation invariance for the full range of 0–360° and six filters for scale-invariance ranging from 55% to 220%) are sufficient to cater to all real-time distortions. The input target’s FT is multiplied with the filters one by one, displayed on SLM and an optical FT taken. Simulation results with out-of-plane rotated images of MBT-Arjun tank as true class and T72 tank as false class (Fig. 14) collected from CVRDE, Chennai, have been shown in Fig. 15. Experimental results are shown in Fig.16, where only one autocorrelation peak has been captured. Fig. 15 shows the CPI plot for true and false class images for the complete out-of-plane rotation. It is evident from the plot that the false class has a CPI value much lower than that of the true class, even in the presence of background.

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5. ADAPTIVE OPTICAL HIGH-RESOLUTION IMAGING SYSTEM FOR LONG-RANGE SURVEILLANCE

Adaptive optics (AO) technique was conceptualized, invented and developed by U.S. defense for imaging of foreign satellites with ground-based telescopes. This technique provides dynamically adaptable diffraction limited corrections to the atmospheric turbulence induced aberrations. Aberrations are deviation to the wavefront shapes from the ideal one. Adaptive Optics employs a Deformable Mirror (DM) and Tip-tilt Mirror (TTM) as a corrector elements in closed-loop and Wavefront Sensor (WS) as aberration measuring sensor. The atmospheric turbulence causes image degradation by aberrating the wavefront globally and locally in a dynamic fashion. The global wavefront tilts are sensed by the Quadrant Sensor (QS) whereas the local wavefront aberrations are sensed by Shack-Hartmann WS (SH-WS) and corresponding compensators are the tip-tilt and deformable mirrors respectively. Wavefront sensing, reconstruction and its compensation in closed-loop is required at high speed (i.e. data update within a millisecond) to mitigate the effects of atmospheric turbulence. Wavefront reconstruction is the brain of the AO system that takes sensed data from the sensor and after reconstruction fed it to the compensators.

At IRDE we are developing long range High-resolution AO imaging system as shown in the Fig 17. To develop such a complex system we characterised atmospheric turbulence for various ranges at Mussoorie and Balasore. Results of the turbulence measurement at ITR Balasore are shown in the Fig.18. Based on the turbulence parameters the system was designed.

5.1 Fast Shack-Hartmann Wavefront Sensor

IRDE has developed a High speed Shack Hartmann Wavefront Sensor. A WS is an instrument used to sense the aberrations (or wavefront error function). A generic
PZT and MEMS technology. Wavefront correctors are characterised with Veeco interferometer in the lab to estimate the influence functions. Wavefront surfaces of MEMs DM are shown in the Fig. 20. MEMs based DM is getting indigenously developed at SSPL.

An AO imaging system based on 200 mm telescope is under integration to obtain high resolution image for a range of about 20 km. In this system QD is used to measure the wavefront errors and corresponding compensator is the TTM. Smeared & Compensated image with TTM is as shown in Fig. 21.

The developed wavefront sensor may also find various applications like in ophthalmology, atmospheric/aero-optical turbulence diagnostics, optical testing, laser beam diagnostics etc. We are exploring its spin off applications for retinal imaging, laser beam diagnostics, testing of optical system assembly etc.

5.2 Tip-tilt and Deformable Mirror System

At IRDE we are developing closed-loop control algorithms for multi-actuator deformable mirrors based on stacked PZT and MEMS technology. Wavefront correctors are characterised with Veeco interferometer in the lab to estimate the influence functions. Wavefront surfaces of MEMs DM are shown in the Fig. 20. MEMs based DM is getting indigenously developed at SSPL.

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AO technology has very wide range of applications, such as it could be used to resolve the very distant big objects like galaxies and very small biological cells. AO compensated examples for astronomical and biological imaging are shown in Figs. 22a and 22b.

AO technology is getting matured and under use for various applications like laser beam delivery, long ranges high-resolution imaging, free space optical communication, ophthalmology, bio-imaging etc. Thus indigenous development of AO technology will be very much useful for defence as well as civil application.
6. EMERGING AREAS OF RESEARCH IN PHOTONICS

In this section some of the new areas in the field of Photonics which are fast emerging have been discussed.

6.1 Silicon Photonics

Silicon is most usable and promising electronic material but could not be exploited in Photonics, as it is not favourable material for photons. To cope with the speed of processing, attentions are being made to exploit the silicon material for Photonics use. Silicon Photonics is a research & development effort to revolutionise computing platforms by manufacturing optical communication devices using traditional CMOS techniques. The integration of optics technology into the computing industry will revolutionize the way computers work and the value that they provide to people. Silicon photonics will provide substantial size, cost, and power savings over traditional optical communication solutions. To “siliconize” photonics, there are six main areas or building blocks for investigation. These include generating the light, selectively guiding and transporting it within the silicon, encoding light, detecting light, packaging the devices and finally, intelligently controlling all of these photonic functions. Intel is working to address these areas, and this research has produced a few recent success stories, including the first continuous-wave silicon laser and the first gigabit speed silicon modulator.

Over time, It is a vision to develop integrated, high-volume silicon photonic chips that could dramatically change the way that enterprises use photonics links for their systems and networks. Simply having photonics could eliminate bandwidth and distance limitations, allowing for radically new flexible architectures capable of processing data more efficiently. Silicon photonics may even have applications...
beyond digital communications, including optical debug of high speed data, expanding wireless networks by transporting analog RF signals, and enabling lower cost lasers for certain biomedical applications.

6.2 Micro-Optics

Micro-optical components enable a designer to reduce the system volume and weight of an optical system. Reduction in system volume and weight of an optical system increases the utility of optical systems manifold. The fabrication of micro-optical components like lenses and gratings uses established techniques used in microelectronics like lithography and direct writing.

Microoptical elements can be classified as (a) refractive (b) diffractive and (c) hybrid. The decision to use the type of component would depend on the problem in hand. The two major categories of application are beam shaping and imaging. In all cases, the most critical parameters refer to the spectrum of the light and the diffraction efficiencies that would be possible. Diffractive optics has thus a strong wavelength dependence even though the wavefront control is possible to a high degree of accuracy giving the designer freedom to generate any type of optical component in a planar format. For broadband spectral applications, diffractive optical elements will have to be combined with refractive optics for controlling its chromatic aberration.

Applications

1. Beam shaping: Beam shaping is the homogenization of the output beam from a laser using cylindrical, toric, aspheric lenses or axicons.
2. Fan-out gratings: These elements split an incoming beam into an array of diffraction order of equal intensity. They are of two type- Damman gratings and continuous surface relief fan-out. Damman gratings offer 80% efficiency can be fabricated by lithographic techniques using a binary approach. Continuous surface relief fan-out gratings offer efficiencies nearing 95% and can be fabricated using direct write technology.
3. Interconnects: Interconnects signifies connection between independent optical channels in parallel and using microlens array.
4. Imaging: Microoptical components like microlenses, polarizers and filters are used for macro imaging and for realising image transfer systems. The other imaging application of microoptics is integral photography. Integral photography is a 3-D technique using incoherent light microlens arrays. Each lens in the array sees the object a little differently resulting in a multiple image formed from multiple angles quite close to each other. The superposition of these images give a 3-D effect.

6.3 Photonic Crystal

Photonic band gap structures consist of a block of transparent dielectric material that contains a number of tiny air holes arranged in a lattice pattern. As the photons pass through regions of high refractive index - the dielectric - interspersed with regions of low refractive index - the air holes most of the light is confined either within the dielectric material or the air holes. This confinement results in the formation of allowed energy regions separated by a forbidden region - the so-called photonic band gap. It is possible to create energy levels in the photonic band gap by changing the size of a few air holes in the material. In this case, the diameter of the air holes is a critical parameter, together with the contrast in refractive index throughout the material. A rough estimate of the spacing between the air holes (or the lattice size) is given by the wavelength of the light divided by the refractive index of the dielectric material.

The potential of photonic-crystal structures was first realized in 1987 by Eli Yablonovitch, then at Bell Communications Research, in New Jersey. A few years later in 1991, Yablonovitch and co-workers produced the first photonic crystal by mechanically drilling holes a millimetre in diameter into a block of material with a refractive index of 3.6. The material, which became known as “Yablonovite”, prevented microwaves from propagating in any direction - in other words, it exhibited a 3-D photonic band gap. In spite of this success, it has taken over a decade to fabricate photonic crystals that work in the near-infrared (780-3000 nm) and visible (450-750 nm) regions of the spectrum. The main challenge has been to find suitable materials and processing techniques to fabricate structures that are about a thousandth the size of microwave crystals. To be able to create photonic crystals for optical devices, we need to use state-of-the-art semiconductor-microfabrication techniques with their associated high production costs and investment. For this reason computer modelling of prospective photonic-crystal structures is also a very important area of research, as it may prevent expensive fabrication errors later.

Applications

1. Optical-communications: Photonic crystals could address many of the problems that currently limit the speed and capacity of optical-communications networks. For example, these structures could be used to create novel LEDs and lasers that emit light in a very narrow wavelength range, together with highly selective optical filters that could be integrated on a chip.
2. Narrow-linewidth lasers: Photonic crystals built from photoemissive materials, such as III-V semiconductors and glasses doped with rare-earth atoms, can also be used to make narrow-linewidth lasers that could potentially be integrated with other components in an optical-communications system. The lasers are made by introducing a small number of holes that are slightly smaller or larger than the other holes in the photonic-crystal lattice.
3. Narrow-channel waveguide: It is possible to form a narrow-channel waveguide within a photonic crystal by removing a row of holes from an otherwise regular pattern. Light will be confined within the line of defects for wavelengths that lie within the band gap of the surrounding photonic crystal.
4. Photonic-crystal fibres: Photonic-crystal fibres has a regular lattice of air cores running along its length
and transmits a wide range of wavelengths without suffering from dispersion. The fibre has the unusual property that it transmits a single mode of light, even if the diameter of the core is very large.

6.4 Meta-materials

Like photonic crystals, metamaterials owe their electromagnetic properties to their physical structure rather than to their chemical composition. In contrast to photonic crystals the defining structure is on a scale much less than the wavelength of relevant radiation, typical by a factor of 10 or more. The properties of a conventional material are derived from their constituent atoms whereas that of a metamaterial are derived from their constituent units. The most sought after application of metamaterials has been to realise negative refractive index. Here the challenge is to realise the Veselago prescription for negative refractive refraction \( \varepsilon < 0, \mu < 0 \) where \( \varepsilon \) and \( \mu \) represent permittivity and permeability. At optical frequencies designs have been realised based on a double resonator consisting of two parallel metal rods. These structures have odd and even resonances tuned to coincide, one giving a negative magnetic and other giving a negative electric response.

Applications

1. Superlens: Metamaterials with the property of negative refractive index acts as a perfect lens (superlens) in the sense that it makes it possible to overcome the diffraction limit of resolution, caused by wave nature of light. Such a lens can not only focus propagating rays but also finer details of near field electromagnetic waves, which are evanescent, i.e. they do not propagate.

2. Cloaking: Metamaterials can be used to control electromagnetic field. This makes it possible to cloak an object by guiding the flow of electromagnetic field around it and thereby making it invisible to an observer. Early experiments at microwave frequencies have shown that it is possible to design a metamaterial around an object such that an incoming wave can be totally reconstructed on the other side of the same object. In a sense the metamaterial acts like a cloak that makes the object inside invisible to the outside. To achieve cloaking at optical frequencies, researchers have suggested the design of a new non-magnetic cloak consisting of wires all of which are perpendicular to cylinders inner and outer interfaces.

7. CONCLUSION

With the rapid advancement in materials, solid state miniature devices, compact laser sources, Photonics technologies are finding increasing applications in all spheres of life both for military & civilian use. Considerable research in the field of Photonics is being carried out in Academic Institutions, R&D centres in the country. But we do not have any major industry for Photonics devices & components. Nationwide consolidated efforts are required to get the benefits of research in Photonics for the societal missions.

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