Advancements in Optical Communication Research: A Review of India's Progress

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(Invited Paper)

***Abstract*—With the increasing use of internet and mobile phones, the capacity of the backbone optical communication link has been continually growing across the world and especially in India. The total optical fiber cable deployed for the BharatNet initiative of Government of India is expected to increase from 3.4 million km to 5 million km in 2024–25 just for providing last-mile connectivity. Considering this deep proliferation, this article attempts to capture the diverse research carried out in India in the domain of optical communication.**

***Index Terms*—Fiber optics, coherent communication, photonic integrated circuits, optoelectronics, quantum key distribution, India, optical communication.**

I. Introduction

THE total number of internet users across the globe is projected to grow from 3.9 billion to 5.3 billion by 2023 at a compound annual growth rate of 6% [1]. As per the survey conducted by the Internet and Mobile Association of India (IAMAI) and Kantar, internet users in India have registered the highest-ever presence of 759 million in 2022, which is over half of our country's total population, and is expected to reach 900 million by the year of 2025 [2]. With more than 0.3 million 5G base stations deployed over the last year, India has recorded the fastest roll out 5G services. Fiber optic communication system is the backbone for all mobile data and internet traffic [3]. With this deep proliferation of internet and mobile networks, the optical transmission systems are expected to experience an increase in demand for capacity by orders of magnitude. The growth in capacity of optical fiber links were facilitated over the initial couple of decades of fiber deployment with Erbium-Doped Fiber Amplifiers (EDFAs), Wavelength-Division Multiplexing (WDM), higher signalling rates, electronic dispersion compensation, and Digital Signal Procesing (DSP) both at transmitter and receiver. The capacity enhancement over the past two decades has been possible by packing more bits in a symbol slot by adopting advanced modulation formats, and by transmitting independent data in orthogonal polarization, pulse shaping, probabilistic and constellation shaping, thus allowing improved data rates without expanding the bandwidth of the deployed optical amplifiers. The current state-of-art of high spectral efficiency systems have already steered towards coherent optical communication, which employs advanced modulation formats such as polarisation multiplexed Quadrature Amplitude Modulation (QAM) with pulse shaping.

In case of India, the deployment of optical fibers and choice of transmission capacities have taken a natural progression based on the demands of the national backbone networks and metro networks, which are operated by both Government and private operators. In order to meet the demand in capacity and to bridge the digital divide, optical fiber cables have been deployed to reach the remotest villages, through the Government of India's "BharatNet" project- which is one of the biggest rural telecom projects in the world [4]. It is being implemented with a goal of providing non-discriminatory access to broadband connectivity to all the telecom service providers. Under the BharatNet Project 1,77,550 Gram Panchayats (GPs - village headquarters) have been made service-ready until June 2022 with broadband speeds of 50 Mbps [5]. For this project, the total optical fiber cable laid is approximately 3.4 million km as on June 2022, and is expected to be increased up to 5 million km by 2024–25 [5]. The capacities of these networks are also expected to be upgraded in the next few years. Going forward, a humongous green field deployment is expected in India to provide last mile connectivity to about 0.62 million villages, in addition to the fiber fronthaul for 5G and beyond. Given this context, it is only imperative to explore the key research activities in the country in the context of changing phases of optical communication.

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II. History and Landscape

India boasts a long history of important contributions in the global development of science and technology in general and in the development of optics and photonics in particular. The word photonics originate from the word photon, which represents the fundamental indivisible quantum of light. All photons (or Bosons in general) follow the Bose-Einstein statistics, which was primarily worked out by an Indian scientist, Satyendra Nath Bose in the first half of the twentieth century. Around the same time in 1928, another Indian scientist, Chandrasekhara Venkata Raman made a remarkable discovery on the nature of scattering of light by tiny particles [6]. This discovery, known as the Raman effect, has been a cornerstone for numerous developments in the discipline of optics and photonics and earned him the Nobel Prize in Physics in 1930. Another fundamental achievement pertinent to the development of communication systems was realized by Jagadish Chandra Bose, an eminent Indian physicist of the twentieth century. After an unfortunate early demise of Heinrich Hertz in 1894 who had experimentally confirmed the existence of electromagnetic waves (as theoretically predicted by James Clerk Maxwell in the 1870 s), and had set the stage for future endeavours, Bose was the first to produce and control electromagnetic waves at frequencies as high as 60 GHz, in the 1890s [7]. This was an important development for that time and opened a number of possibilities for the next generation of communication systems relying on radio waves. While radio wave based wireless communication gained a lot of attention in the first half of the twentieth century, preliminary developments during the 1950 s, indicated the possibility of high-capacity communication using light, over thin dielectric wires made of high purity silica glass, which later came to be known as optical fiber. In fact, the term “fiber optics”, was coined by an Indian-American physicist, Narinder Kapany, in 1960 [8]. His seminal works with Harold Hopkins at the Imperial College London, in the 1950 s and 60 s laid the foundation of the new field of fiber optics. As discussed in Section 1, today fiber optic networks form the backbone of our global internet and is at the heart of modern communication technologies. Also, the development of high speed wifi connections and 4 G internet networks we have today, owe a great deal to the invention of Multiple Input Multiple Output (MIMO) radio wave antennas in 1993 by Arogyaswami Paulraj and Thomas Kailath, two Indian-American inventors [9]. All these different contributions throughout the past century or so, indicate a significant impact made by the Indian scientific community in optics in the global stage and naturally we inherit the responsibility of setting a high standard of future research in optics and photonics in India.

The breakthrough of invention of fiber in 1970 [10] inspired the formation of India’s first fiber optics group, which awarded its inaugural PhD degree in 1973 at Indian Institute of Technology (IIT) Delhi. Since then, different research groups sprung across the country- in the IITs, and Government research laboratories and other central and state universities.

The Photonics group at IIT Madras conducts experimental and theoretical research in the domains of photonic integrated circuits, optical MEMs, diffractive optics, plasmonics, optical sensors, optical communication and networks, optical signal processing, fiber lasers, quantum communication and computing. Many prominent scientists worldwide - especially the Indian diaspora- attribute their understanding of the fundamentals of the subject to their training in Indian institutes during their formative years. In addition to several start-ups in this domain, India can also boast a strong industry presence, including Sterlite Technologies Limited and Tejas Networks who significantly contribute to the deployment of optical fiber and network equipments in India and elsewhere.

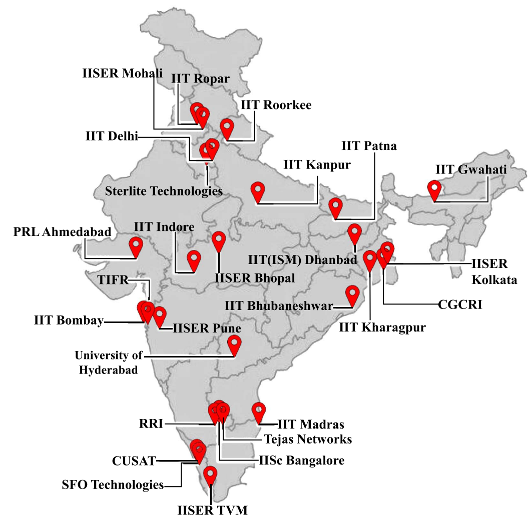

Fig. 1. Illustration of research institutes and industries involved in research in optics and photonics in India.

The locations of major institutes involved in research in optics and photonics in India are shown in Fig. 1. A wide range of research related to Photonics is carried out in the institutes listed above and other institutes, whose names are not included due to paucity of space. In the next section, we attempt to provide a glimpse of the research activities in the area of optical subsystems, systems and networks from these academic and research institutes.

III. Optical Subsystems, Systems and Networks

A. Optoelectronics and Photonic Integrated Circuits

Two centres in southern India - the Center for Nanoscience and Engineering (CENSE) at Indian Institute of Science (IISc) Bangalore and the Center for Programmable Integrated Circuits and Systems (CPPICS) at IIT Madras are the main hubs with state-of-the-art facilities for fabrication, characterisation and packaging of photonic integrated circuits with ComplementaryMetal CMOS compatible materials such as silicon on insulator and silicon nitride along with ability for monolithic or heterogeneous/hybrid integration. In addition, we are also seeing some agressive start-ups coming up in this space for fabless design and packaging of photonic integrated circuits for classical and quantum applications. Research level experimental expertise for quantum well semiconductor based lasers exists in IITs at Kanpur, Mumbai, Delhi and in Tata Institute of Fundamental Research (TIFR) Mumbai. Light Emitting Diodes (LEDs) are manufactured through the utilization of nanostructured materials synthesized using metal organic vapor-phase epitaxy facilities at TIFR Bombay, as reported in the work by De et al. in 2011 [11]. Notably, the same research group made a significant contribution to pandemic response through their study on the decontamination of N95 respirators [12]. White light emitter and blue emitter based on highly efficient quantum dots are fabricated for optoelectronic devices in IISc Bangalore [13], [14]. Other sources based on a second and third harmonic generation is reported in the wavelength range 1500–1600 nm using an amorphous silicon based metasurface [15] in IISc Bangalore and the same group has also explored a hybrid LED-laser source for 5G testbed for visible light communication [16]. Frequency comb source based on microring resonator is designed in IIT Kharagpur [17]. The simultaneous generation of harmonics - second at 780 nm, third at 520 nm and sixth-order at 260 nm a 10 mm long silica nanowire is reported by Indian Institute of Science Education and Research (IISER), Thiruvananthapuram. Mode-locked lasers have been developed for narrow linewidth, ultra-short pulsed (ps-fs regime) at higher repetition rate ($>$ MHz) for applications in optical communication and Microwave Photonics in IIT Madras. This group has also packaged and commercialized fiber lasers. Photonic crystal based lasing and erbium-doped fiber lasing are also studied in IIT Kanpur. Apart from sources, photodetectors are also developed based on semiconductor waveguide (InGaAsP/InP) in IIT Kanpur and based on p-NiO/n-Si heterojunction using pulsed laser deposition technique in IIT Roorkee [18]. A broadband and high sensitivity perovskite photodetectors are developed by a IIT Bombay reserach group [19] and a compact on-chip photodetector in 850 nm wavelength band for communication is demonstrated by a group at CENSE, IISc [20]. Electro-Optic modulators based on integrated circuits are also fabricated in GHz range in IIT Kanpur and IISc Bangalore [21]. The central facilities for fabrication and characterization available in India is open for other universities and institutes using a National portal - Indian Science, Technology and Engineering Map facility (I-STEM) provided by Govt. of India. Commercial level production of optoelectronic and photonic integrated circuits are expected to gain impetus in the near future.

B. Fiber-Optics

In the area of fiber-optics, many research groups work on the design of optical fibers for various applications and also fiber-based components such as fiber couplers/splitter, fiber-coupled sources. All fiber based component such as fiber couplers, photonic lanterns, wavelength-division multiplexers are developed in-house at IIT Delhi [22], [23]. Specialty fibers such as multi-core fibers, few mode fibers are explored for their application in space division multiplexing in our lab - optical communication engineering and networking at IIT Madras. In our group, the dispersion engineered fibers are designed and tested for parametric oscillator by suppressing stimulated Brillouin scattering as a part of a bilateral Indo-Russian Project [24]. Our work is in collaboration with industry partner- Sterlite Technology Limited (STL) who manufactures optical fibers of commercial grade, starting from the perform. HFCL is another significant industry player in the domain of commercial fibers and cables. Photonic Crystal Fibers (PCFs) are designed and fabricated at IIT Kharagpur and Central Glass and Ceramic Research Institute (CGCRI). Ultra-low loss fiber is studied based on anti-resonance properties of hollow core fiber for communication experiments in IISc Bangalore [25]. A supercontinuum source based on their fabricated PCF is commercialized jointly with the industrial partner Vinvish Technologies, Trivandrum, India. SFO technologies in Kochi have a commercial unit for manufacturing several fiber optic components including couplers and optical amplifiers.

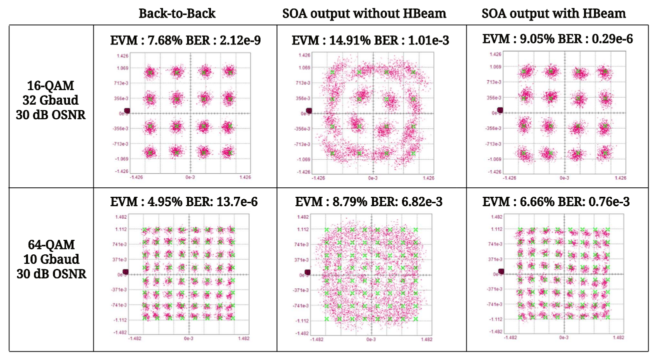

Fig. 2. Illustration of the use of SOA in coherent communication : Constellations for output of SOA for 16-QAM (top) and 64-QAM (bottom) formats in three situations (back-to-back in left column, with SOA but no holding beam in middle column and with SOA with holding beam in right column) when the drive current was 350 mA.

C. Optical Amplifiers

Optical amplifiers play a significant role in the optical communication systems. Doped fibers developed in CGCRI were designed into amplifiers, packaged and commercialised by SFO Technologies Ltd in early 2000 s. One method to increase data rate throughput is to expand the optical bandwidth of amplifiers. Parametric amplifiers serve to minimise the noise and thus improve the reach of data in advanced modulation formats. Our group has demonstrated the potential of using Semiconductor Optical Amplifiers (SOA) for coherent communication, especially useful in the context of ultra-wideband amplification [26]. Fig. 2 shows the results for 16/64 QAM when SOA is used as inline amplifier in coherent communication link. The distortions incurred while amplification are mitigated by employing a strong beam called holding beam (Hbeam) [26]. In addition, compact semiconductor optical amplifiers are also demonstrated to be used as spectral inverters for dispersion healing in the optical domain, which can in turn minimise the requirements on digital signal processing [27].

We also have demonstrated phase sensitive amplifiers with a high gain extinction ratio for potential wide band application for classical and quantum links [26]. An exhaustive review on

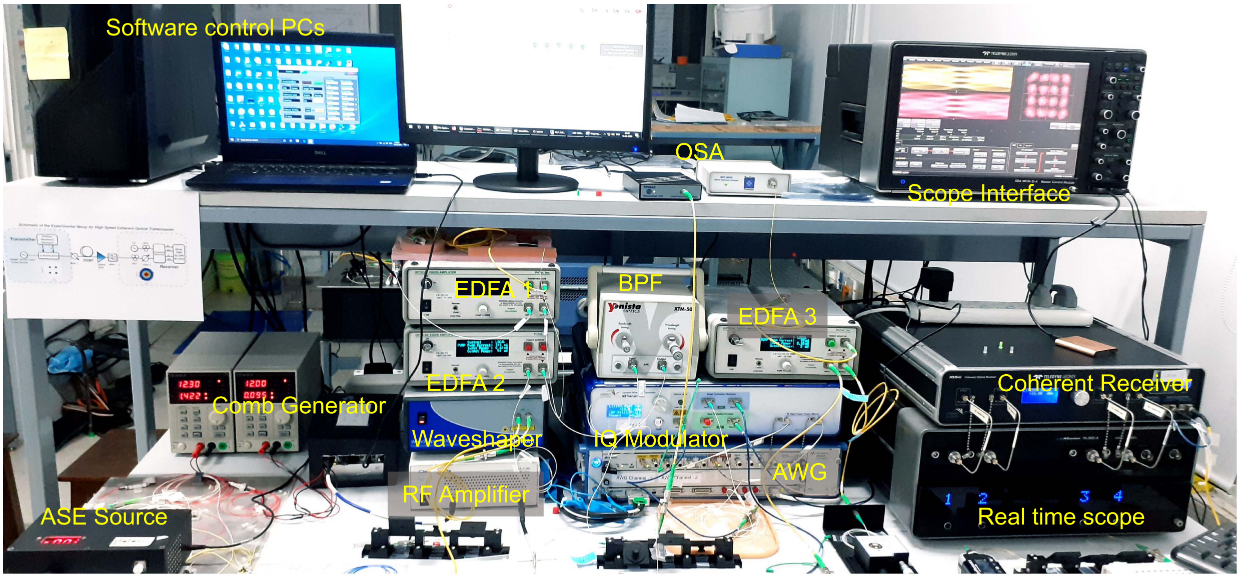

Fig. 3. Experimental setup for the generation, transmission and reception of optical superchannel signals.

the utility of SOAs for optical communication and optical signal processing can be found in [26].

D. Optical Communication and Signal Processing

Optical communication systems have evolved from intensity modulation and direct detection to coherent communication using advanced modulation formats, where information is encoded in the amplitude, phase, and polarisation of the optical carrier [28]. Over the past two decades, this field has witnessed remarkable technological advancement at an incredibly rapid rate with critical advancements made by industry research. While scaling the modulation cardinality, the effect of the impairments in the system becomes critical. Our research group has been extensively working on methods to scale the capacity and developing low complexity Digital Signal Processing (DSP) algorithms to compensate for various impairments. Fig. 3 shows the photograph of the experimental setup at IIT Madras for optical coherent communication, with the ability to inject the desired amount of noise and also a recirculating loop to emulate multi-span transmission. We have demonstrated Tbps data transmission using superchannel, few mode and multi-core fiber transmission in collaboration with Sterlite Technologies Ltd [29], [30]. Fig. 4 shows the superchannel transmission with Fig. 4(a) showing the spectrum of the gain flattened comb line separated by 36 GHz and modulated with 32 GBaud PM-16QAM data and Fig. 4(b) showing the EVM performance of the transmission over 50 km SMF as a function of channel index (increasing wavelength). With this scheme, the spectral efficiency of 7.1 b/s/Hz for 1.024 Tbps data transmission was achieved [30].

We have also demonstrated various DSP algorithms through post processing of experimental data in order to compensate for various impairments in coherent transmission such as widely linear filter for multi-impairment correction [31], carrier phase

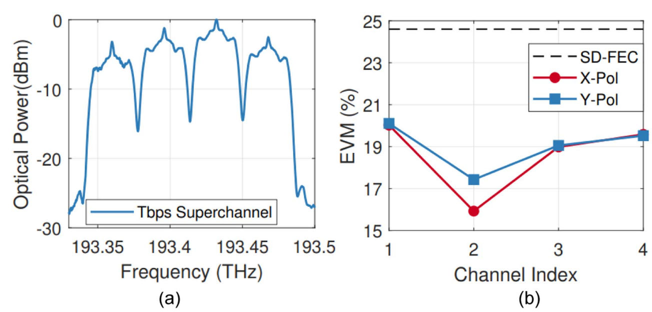

Fig. 4. (a) Optical spectrum of 1.024 Tbps superchannel. (b) EVM of PM-16QAM transmission over gh50 km SMF as a function of channel index.

recovery tolerant to transmitter IQ imbalance [32], Geometric parameter extraction based method for receiver IQ imbalance correction [33], [34], Kalman filter based phase noise correction for OFDM signals [35].

The research group at IIT Bombay has focused on the demonstration of different versions of photonic integrated circuits and analog coherent receiver-based data center interconnects [36], on chip optical equalizers for direct detection links to mitigate inter-symbol-interference [37]. Free space optical communication and networked LiFi is being explored by IIT Delhi. Optical phase modulator based frequency comb and its expansion to C-band through nonlinear effects is demonstrated by IISc.

E. Radio Over Fiber and Microwave Photonics

Transmission of high frequency RF and analog signals through optical fiber is popular for radars and millimeter-wave systems. In addition to transport, the realm of Microwave Photonics lends itself to the generation and signal processing of high frequency modulated/carrier signals in the optical domain with much better signal quality, and higher bandwidth compared to the electronic counterparts.

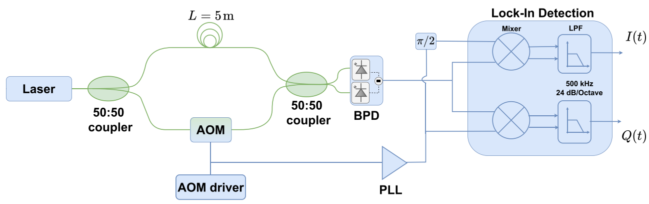

Fig. 5. Schematic showing the experimental setup of the coherent self-heterodyne technique. BPD-balanced photodiode. AOM-Acousto optic modulator.

Our group at IIT Madras has made a significant contribution to designing analog Radio over Fiber (RoF) solutions for optical fronthaul - specifically for 5G applications. Multiple techniques for generating and transporting 5G millimeter-wave signals with modulated data are devised which include frequency doubling, quadrupling and optical phase locked loops. We have successfully generated, transported and detected a 100 MHz signal with modulation extended up to 256 QAM at a carrier frequency of 26.4 GHz, with EVM satisfying the 3GPP standards [38]. We have also analysed the performance of analog fronthaul schemes for co-existence of 4 G and different wave forms of 5G [39]. We have created a software tool for designing analog optical links of desired specifications such as SFDR and link gain.

In the domain of optical signal processing of RF signals, we are currently developing photonic Analog-to-Digital Converters (ADCs) to overcome the limitations of traditional electronic ADCs. The team attempts translational research this domain with prototypes developed for fiber-based optical clocks with a timing jitter of approximately 60 fs [40], Sub-Nyquist samplers operating in S band with a 1 GHz fiber laser [41], and a single-shot time-stretched photonic ADC with an effective bandwidth twelve times greater than the corresponding Electronic ADCs [42]. Our team has also demonstrated a novel deep learning-aided time-stretch photonic front-end architecture to overcome device-dependent distortions. An improvement of 24.4 dB in Signal-to-Noise and Distortion Ratio (SNDR) is observed for a time stretched photonic ADC with a stretch factor of 3.132 with the use of trained model. Associated technologies such as dither-free multi-channel any-point bias controllers, pulse-pickers and interleavers to control the repetition rate of optical clocks are developed by our team [43], [44]. Accurate measurement of phase noise of low-linewidth lasers is a critical requirement for coherent communication, distributed acoustic sensors, microwave photonic and quantum applications. A Coherent Self-Heterodyne (CSHD) technique, that can measure the phase noise up to 10^{-2} Hz^2/Hz at 1 kHz offset is demonstrated by our team. The schematic of the experimental setup for CSHD is shown in Fig. 5.

In the CSHD technique, light from the laser to be tested is split using a polarisaition maintaining coupler; one of the outputs is delayed (within the coherence length) while the other is frequency shifted, and then combined. Such an interferometer configuration allows for a self-referenced technique to measure the phase noise. A lock-in detection technique is used to record the instantaneous phase of the laser. The power spectral density of the phase noise (referred to as the FM noise spectra) of

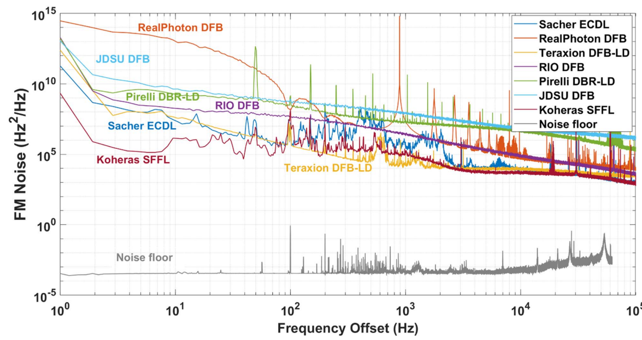

Fig. 6. FM noise spectrum of different types of narrow linewidth laser diodes.

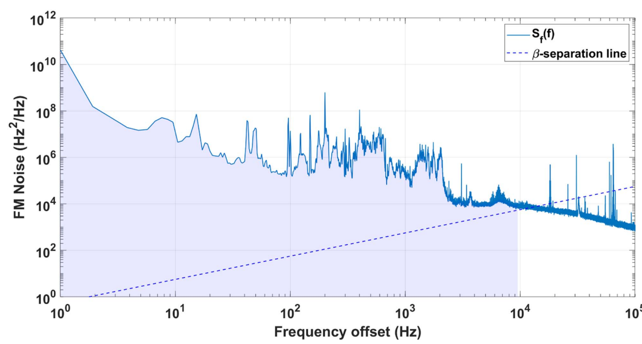

Fig. 7. Linewidth estimation using β-separation line analysis for an External Cavity Diode Laser (ECDL).

multiple laser sources available in the lab and operated using standard laser drivers are measured and compared, shown in Fig. 6. The estimated noise floor of the measurement setup is also marked in the same plot, proving that the measurement is not limited by the noise.

The β separation line method is used to quantify the linewidth from the power spectral density (PSD) of phase noise; this is a geometric approach used to identify the region of high modulation index ($\beta > 1$) that contributes predominantly to the laser linewidth [45]. The PSD of phase noise is divided into two regions by the $\beta = 1$ line, each affecting the laser linewidth differently. Only the parts of the FM noise spectra (shaded region in Fig. 7) where $S_f(f) > \frac{8ln(2)}{\pi^2} f$ is expected to contribute to the laser linewidth, where f is the frequency offset [45]. The full width half maximum is then calculated as $\sqrt{8ln(2)A}$, where A is the area under the curve within the shaded region. For the laser under test shown in Fig. 7), the estimated linewidth is 10 kHz is matching closely with the datasheet. This phase noise analyser is packaged into a prototype and hence can be easily transported for measurements. We have been carrying out prototyping at the laboratory level for other experiments as well. A collage of all the prototypes developed from our lab is shown in Fig 8.

The Ultrafast Optical Communications and High-performance Integrated Photonics (UFO-CHIP) group at IIT Delhi demonstrated phase shifters, electromagnetically induced transparency (EIT)-like filters, reconfigurable bandpass and bandstop filters up to 1 GHz, and linearised analog photonic links using

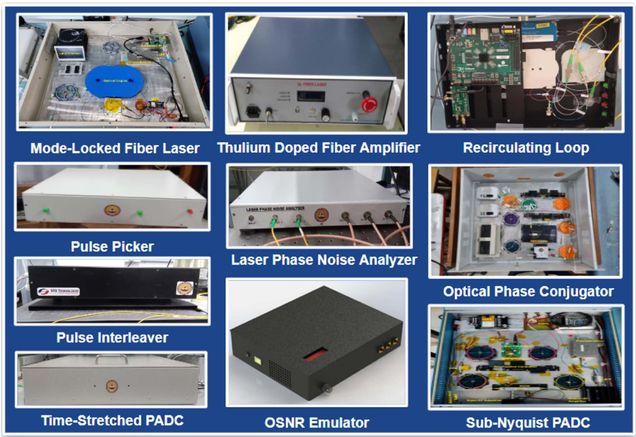

Fig. 8. Prototypes developed at IIT Madras in the domain of optical communication.

SBS. The group has also demonstrated multiple target detection with photonic radar concepts, with a range resolution of < 15 cm, multi-band generation and band-selection with SBS-based filters, and high-bandwidth signal generation and Wavelength Division Multiplexing (WDM) based RoF solutions for 5G fronthaul [46].

The laboratory for Photonics and Nonlinear Optics in Nanostructure (PHONON) at IISER, Thiruvananthapuram is geared towards realizing small footprint frequency combs from visible to mid-IR wavelength region and developing advanced techniques for wideband, high-resolution photonic processing of microwave signals for applications in RADAR and mobile communications, and electronic warfare. Combining photonic processing with bias control over the phase of microwave signals, they have demonstrated wideband, large extinction microwave photonic notch and band pass filters with dispersion compensation [47], [48], [49].

F. Optical Networking

There are several research groups in India working on different aspects of optical networking. Spectrum allocation in elastic optical networks, link failure protection strategies are studied by research groups at IIT Kanpur [50]; resource allocation for mixed grid optical networks, applying deep/machine learning methods to achieve quality aware resource provisioning, nonlinear-impairment-aware proactive de-fragmentation are done at IIIT Delhi [51], energy efficiency of backbone and access networks are studied at IIT Kharagpur [52], application of machine learning in order to maximize performance of distributed RAMAN amplifier for WDM network applications [53], deep learning assisted estimation of Quality of Transmission in optical transport networks [54] is done at IIT ISM Dhanbad. There are several industry players in this domain, including Tejas Networks which global networking product company, who are responsible for design and deployment of the networking infrastructure in the country.

G. Quantum Key Distribution (QKD)

In recent years, QKD has been widely accepted as a promising technology to realize secure networks as it relies on the fundamental principles of quantum mechanics. The center for quantum information communication and computing (CQuICC) at IIT Madras is making significant contributions in this domain with the design of Frequency Coded (FC)-QKD system, Differential Phase Shift (DPS)-QKD up to 105 km [55], [56], Cohrent One-Way (COW)-QKD, up to 150 km [57], and Measurement Device Independent (MDI)-QKD. This research group is also working on building a Quantum Random Number Generation (QRNG), entangled sources, detectors, quantum secret sharing, quantum inspired photonic computing and Continuous Variable (CV-QKD) system with field implementation of a fiber-based QKD network (star topology) with a 17% quantum bit error rate (QBER) in Chennai, India last year in collaboration with ERNET, CDAC and SETS [58]. The Defence Research Development Organisation (DRDO) and IIT Delhi have successfully demonstrated a 100 km QKD link between Prayagraj and Vindhyachal in Uttar Pradesh [59], [60]. This achievement showcased the nation's self-developed technology for securely transferring keys, establishing a foundation for military-level communication security key hierarchy. Indian scientists from the Space Applications Centre (SAC) and the Physical Research Laboratory (PRL) in Ahmedabad have successfully demonstrated the use of quantum entanglement-based real-time QKD across a 300-meter atmospheric channel [61]. This breakthrough also encompassed the secure transmission of quantum-protected text and images, as well as quantum-assisted two-way video calling. Routing and resource allocation problems of QKD links along with AI/ML techniques for solving the complex decision-making problem of QKD-secured optical networks are studied by IIT Indore [62]. The Fiber-Optics, Quantum and Nano-Photonics (FOQNP) group from IIT Kharagpur works on quantum communication for satellite communication, key distribution and quantum random number generation, both theoretically and experimentally [63]. The Light and Matter Physics (LAMP) team at Raman Research Institute (RRI), Bengaluru, is actively involved in the creation of single photon sources using spontaneous parametric down-conversion, and the utilization of these sources in critical areas like fundamental quantum mechanics tests, quantum information and computing, and quantum communication [64], [65]. There are several start-ups who are actively involved in the commercialisation of quantum key distribution technologies.

IV. Outreach

Most of the academic and research institutes cultivate local student chapters of various professional organizations, including Optica, IEEE, SPIE, and Optical Society of India (OSI). These chapters undertake outreach initiatives, venturing into rural corners of India to kindle curiosity and enthusiasm for scientific disciplines with a focus on optics. Alongside, they organize research seminars, travel lectures, and student-led conferences. These initiatives aim to inform students about diverse career opportunities and research prospects available within the realm

Fig. 9. Photographs from the outreach programs conducted by Optica student chapter of IIT Madras demonstarting basic optics related experiments to high school students.

of Optics. One example of this commitment can be observed through the student chapter at IIT Madras, whose activities are represented in Fig. 9. This collection of photographs portrays various events organized by the chapter, reflecting their unwavering dedication to fostering Optics education and engagement. Through the endeavors of such student chapters, a robust foundation is being laid for the advancement of Optics education, outreach, and career development throughout the country.

V. Globalization of Optical Sciences

A. Books, Journals and Online Courses

The photonics research community in India has been making impact on the global stage. Historically, this was initiated through Sir C V Raman's groundbreaking work at the Indian Association for the Cultivation of Sciences (IACS), established in 1876 in Kolkata. The Nobel laureate conducted research on the Raman effect, which was initially published in the Indian Journal of Physics [66] a publication of IACS. Since then, this research community has made invaluable contributions to the global advancement of Optics and Photonics. Professor Ajoy Ghatak's books, including "Quantum Mechanics: Theory and Applications", "Optical Electronics," "Fiber Optics" [67], and "Lasers," along with his popular book on Albert Einstein, are widely used worldwide. His book titled "Optics" is now in its seventh edition, with previous editions translated into Mandarin and Persian.

The Optical Society of India, established in 1965, publishes the international journal Journal of Optics [68], which releases quarterly issues hosting research papers across all branches of optical physics and technology. The National Program on Technology Enhanced Learning (NPTEL), initiated in 2003, is an Indian e-learning platform for university level STEM subjects. It is a collaborative effort between IITs and IISc and is funded by the Ministry of Education, Govt. of India. The central idea is to provide open access to recorded lectures from member institutes, conduct MOOC courses with proctored examinations. The platform offers various courses on Optics and Photonics, accessible to students worldwide at no cost. Courses such as "Introduction to Photonics," "Integrated Photonics Devices and Circuits," "Fiber Optic Communication Technology," and "Optical Engineering" by faculty at IIT Madras, "Semiconductor Opto-electronics" and "Quantum Electronics" by faculty from IIT Delhi, and "Integrated Photonics Devices," "Modern Optics", are some of the offerings appreciated by students globally.

B. International and National Conferences/Workshops

Efforts to expand the research community and foster a research culture specifically in the area of fiber optics began in the 1980 s through training courses and workshops, and this continues even today. The International Conference on Fiber Optics and Photonics, known popularly as PHOTONICS, stands as a premier biennial conference in the rapidly evolving realm of Photonic science and technology. Throughout these years, esteemed global experts have graced the event, inaugurating with keynote addresses from Charles Kao and Narinder Singh Kapany in the inaugural and subsequent editions of PHOTONICS. In alternating years, a complementary biennial workshop series, named the Workshop on Recent Advances in Photonics (WRAP), has been consistently held since 2013. Renowned international societies, including IEEE, Optica, and SPIE, have significantly contributed to the success of these conferences. The Optical Society of India organises an annual symposium that extends invitations to researchers worldwide The Government of India's Department of Atomic Energy organizes the National Laser Symposium annually, facilitated by the Raja Ramana Center for Advanced Technology. These efforts have facilitated national and international collaborations within the academia, industry, and at governmental levels, contributing to the expansion of the industry and promoting the establishment of start-ups.

C. Opportunities for International Collaborations

Innovative research in a topic as interdisciplinary as optical communication blossoms best through collaborations; several funding opportunities exist for that. The Department of Science and Technology, the Science and Engineering Board, the Indo-French Center for the promotion of advanced research, the German Academic Exchange Service, the United States India Educational Foundation, the Shastri Indo-Canadian institute, U.K.-India Education and Research Initiative are some examples of organisations/initiatives, who with their corresponding counter parts in the collaborating countries provide opportunities for funding for research exchange. In addition, there are specific programs such as Scheme for Promotion of Academic and Research Collaboration (SPARC) and Visiting Advanced Joint Research Faculty (VAJRA), VAIshwik BHArtiya Vaigyanik (VAIBHAV) fellowships that are specifically targeted to welcome international experts - faculty, post-doc and the students from outside India to be hosted in one of the Indian Universities in order to accelerate collaborations. The Prime Ministers Research Fellowship offered to the Indian research scholars allows them to carry out travel and research in collaborating international Universities.

VI. Conclusion

This article captures the progress of research in the domain of optical communication in India in general and at IIT Madras in particular. There are significant research efforts in the domain of optoelectronics, optical communication systems, RFoF, microwave photonics, classical and quantum networking. With the national missions on quantum technologies and semiconductors, the contributions from India are only expected to grow. Several major academia-industry consortia are being funded by the Department of Telecommunication, Govt. of India this year, which include the 6 G consortium and Advanced Optical Testbed consortium with the goal of technology design, development, and commercialization of telecommunication products and solutions. These are directed towards indigenization and thus facilitating affordable broadband in rural and remote areas of the country.

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