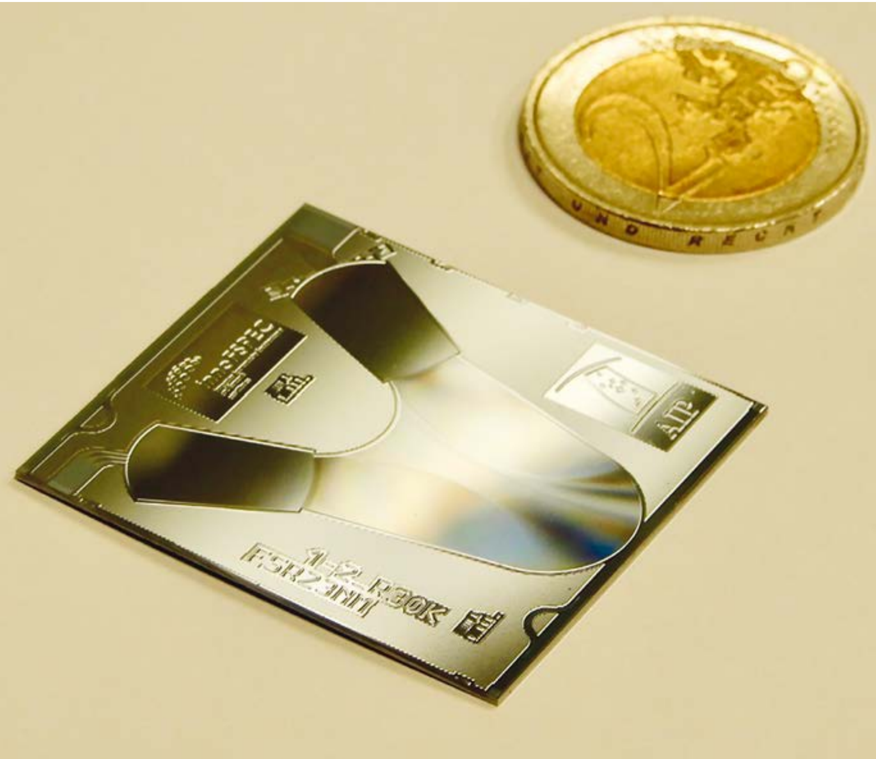
ASTROPHOTONICS:
PROCESSING STARLIGHT



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The field of astrophotonics has been fostering photonic innovations critical and unique to astronomical applications for several years. As we are about to embark on the new era of extremely large telescopes, astrophotonics is poised to become an integral part of the next generation astronomical instruments.

◂ Astrophotonic chip developed at innoFSPEC (Image Credit: A. Stoll)

Astronomical observations enable a continuously increasing understanding of our universe, its evolution and our place within. To unravel its secrets, cutting-edge optical systems and instruments are required to guide, detect and analyze light. High resolution images of stars around the center of the Milky Way have confirmed the existence of a supermassive black hole in the center of our galaxy. This phenomenal discovery was honored by the 2020 Nobel prize in Physics. This groundbreaking work was contributed by GRAVITY [1], an instrument at ESO's Very Large Telescope (VLT). GRAVITY utilises an integrated photonic chip that combines light from four telescopes at the VLT. For future instruments, photonics in astronomy will play an increasingly important role along the beam path.

The next generation of large telescopes

Ground-based astronomy is just about to enter a very exciting era: the world's three largest telescopes (Extremely Large Telescope (ELT): 39 m, Thirty Meter Telescope (TMT): 30 m and Giant Magellan Telescope (GMT): seven 8.4 m diameter primary segments) are planned to be commissioned in the coming decade. To keep up with these capabilities, astronomical instruments have to undergo a drastic transformation. Today's largest telescopes predominantly have instruments that consist of conventional optics. Upscaling these instruments and optics systems in line with future large telescopes, however, will be structurally and economically challenging and unsustainable. **The extraordinary demands on astronomical instruments can be approached with integrated photonics**, owing to their small footprint, flexibility to manipulate light, and ease of mass-fabrication. An additional technological enabler has been the demonstration of the successful coupling of light from Subaru extreme Adaptive Optics (AO) system to a single mode fiber [2]. As the large telescopes are pushing the limits of AO to the near-diffraction-limit, the AO-corrected light can be captured by these photonic devices efficiently using fibers.

Astrophotonics is an interface of photonics and astronomy. This rapidly growing field offers a broad range of optical solutions encompassing sky background filtering, high resolution imaging and spectroscopy. Over the last few decades, there have been promising developments in laboratory tests as well as several on-sky demonstrations of a wide spectrum of fiber and on-chip photonic devices, such as photonic lanterns, complex Bragg gratings, pupil remappers, beam combiners / interferometers, photonic spectrographs, and frequency combs [3]. A possible device chain based on astrophotonics is shown in Figure 1.

Astrophotonics research at innoFSPEC

The astrophotonics group at the research and innovation center, innoFSPEC Potsdam, Germany, is dedicated to the research and development of photonics solutions for ground-based astronomical applications in the near-infrared (NIR). It is one of the few institutes worldwide specifically focusing on this topic.

Photonic Lanterns

AO has become an integral part of all modern ground-based telescopes to correct atmospheric effects in the science light from celestial objects, thus preventing image blurring. In order to correct the wavefront distortion, a conventional AO system consists of a wavefront sensor in an active control loop with a deformable mirror. The AO-corrected light is then either sent to a bulk optics system or fed to a multi-mode fiber for further processing. An interesting device that has emerged in astrophotonics is the photonic lantern (PL). This unique fiber-based photonic component exploits the modal properties of the fiber, allowing a low-loss transition from multi-mode to several single-mode fibers -and vice versa. At innoFSPEC, developments of 19 ports of PLs have already been accomplished. As it remains important to find a suitable combination of an AO system and a PL with a realistic number of outputs, innoFSPEC focuses on a low-order AO system in combination with PLs for efficient coupling of light into astrophotonic devices [4].

Complex Bragg Gratings

Ground-based NIR astronomy is adversely affected by the presence of more than 100 narrow hydroxyl (OH) emission lines originating in the Earth's atmosphere. Being several orders higher in intensity than the science light from a distant object, these OH emission lines contribute significantly to the stray light inside the spectrograph, making the measurement of the signals from faint galaxies or stars extremely challenging.

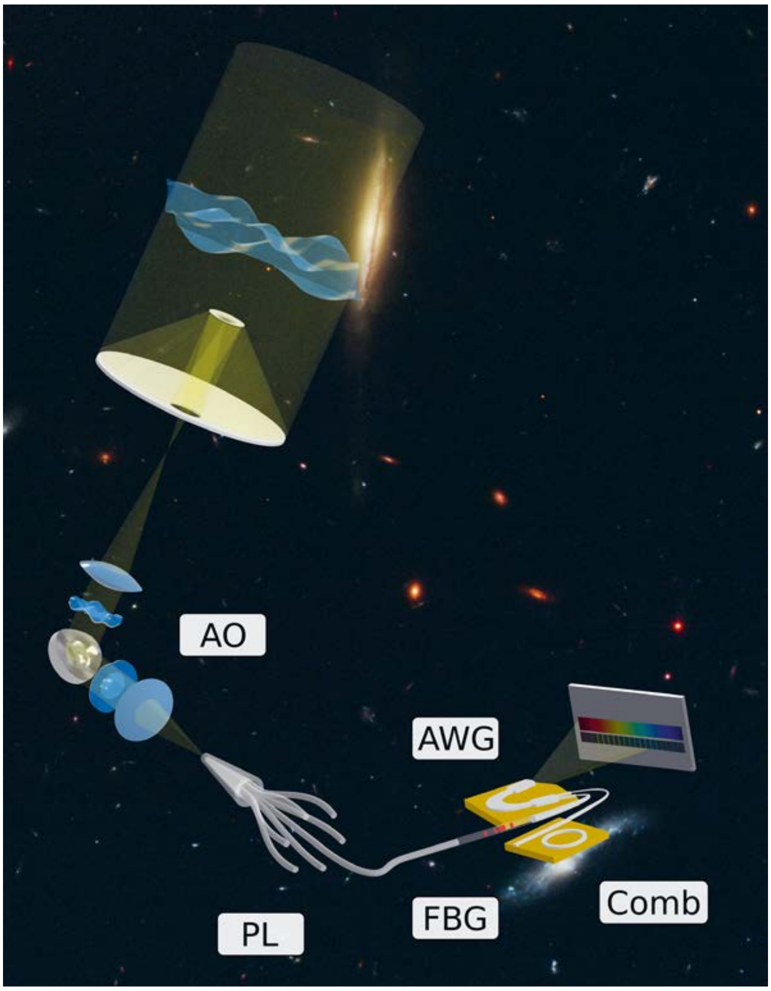
Due to the capability of filtering specific wavelengths with outstanding precision, complex fiber Bragg gratings (FBGs) were first introduced in astronomical applications by Bland-Hawthorn *et al.* [5] as a promising solution over existing technologies. For over three decades, a large number of designs of grating structures in fiber has been explored for many sensing and communication applications. However, the design of a complex FBG consisting of 100 narrow notches suitable for astronomical applications is unique. The fabrication process of these filters is critical, as it demands excellent repeatability in order to get integrated with PLs. In a joint project between innoFSPEC and their collaborators in Australia, the first on-sky demonstration of OH suppression in PRAXIS [6] -a high efficiency NIR spectrograph- has shown promising results. innoFSPEC is also exploring new ways of fabricating these filters using novel complex phase masks.

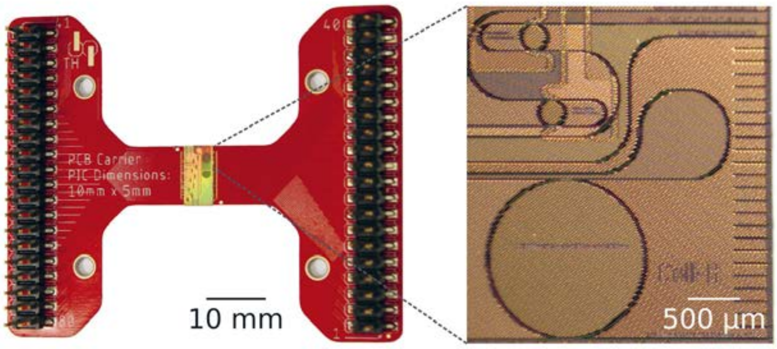
Spectrographs & Frequency Combs

A spectrograph is the heart of an astronomical observation. It allows to study the spectral composition of light or to measure a star's radial velocity, one of the key methods for Exoplanet detection. innoFSPEC is building a miniaturised spectrograph on-a-chip for astronomy based on an arrayed waveguide grating (AWG), a technology originating in the telecommunication industry. Scientists at innoFSPEC have optimised the design specifically for astronomy [7], by which they achieved extraordinarily high resolution (up to 30,000) and throughput (insertion loss of 2 dB). These fiber-fed devices could potentially replace free-space prism or grating optics. innoFSPEC is targeting an on-sky demonstration in 2021.

Frequency combs in astronomy can be used as absolute calibration of high resolution spectrographs. As a calibration source, a frequency comb must have a line spacing and wavelength coverage that matches the

▾ FIG. 1: Schematic showing an astrophotonics device chain for ground-based telescopes. (Image Credit: M. Diab (devices), using a background photo, credit: NASA/ESA, The Hubble Heritage Team and A. Riess (STScI))





▲ **FIG. 2:** A ring-resonator (developed at innoFSPEC) for frequency comb generation. (Image Credit: A.N. Dinkelaker)

requirements of the spectrograph, which is not easy to achieve. There are several technical realizations of frequency combs, and those based on microscopic ring resonators have suitable properties for astronomical calibration [8]. Such a chip-based device –an example is shown in Figure 2- is currently tested in the lab for an upcoming on-sky test at the STELLA robotic telescope. An AWG in combination with a frequency comb could become key element for future compact spectrographs.

Beam Combiners for Interferometry

Using interferometric methods, high angular resolution astronomy can resolve incredibly small details, such as solar-type stars, interacting binaries, or the inner part of planet forming discs. Here, light from several independent telescopes *e.g.*, as part of telescope arrays, such as CHARA or VLTI, is combined interferometrically. Spatial information about the celestial object can be extracted from the interference fringes, thereby achieving the resolution of one large "virtual" telescope with an aperture size of tens to hundreds of meters. This technique has been very successful, from early measurements of star diameters to the position measurements of stars around a Black Hole [1]. The footprint of beam combining optics can be drastically reduced by replacing bulk optics with photonics. In addition to planar devices, 3D photonics are enabled by advances in the technique of laser inscription on glass substrates [9].

Designs from innoFSPEC have already been manufactured, characterised, and tested in collaboration with groups at Politecnico Milano and University of Cologne [10]. The same devices can be used to perform pupil remapping - a technique in which light at different points of the telescope is picked off. By interferometrically overlapping, atmospheric effects can be reduced. First on-sky tests of such a laser written pupil remapper and beam combiner have been performed in 2019.

Outlook

As astrophotonics continues to foster photonic innovations critical and unique to photon-starved astronomical applications, it is exciting to see how some of these devices have already started appealing to other fields of science and technology. In future, astrophotonics might find their place in quantum technology, advanced communication systems, or space-based instruments.

Through laboratory characterization, iterative component developments and on-sky demonstrations, astrophotonics will continue to gain in performance and maturity. The continuous progress in manufacturing methods enables improved functionality and more innovations in the coming years. As the success of GRAVITY marks the importance for photonics in astronomy, we expect to see astrophotonics getting integrated in the design of future instruments, especially for the next generation of large telescopes, paving the way for new and exciting discoveries of our universe. ■

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