Snowmass2021 - Letter of Interest

Pushing Back the Cosmic Frontier with Photonic Technologies for Ground-Based Infrared Astronomy

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

☑ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☑ (CF3) Dark Matter: Cosmic Probes
☑ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☑ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☑ (IF2) Instrumentation: Photon Detectors

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Abstract: (maximum 200 words)
Emission in the upper atmosphere from hydroxyl (OH) molecules impedes accurate observations of astronomical objects. Orbiting observatories are one possible solution to this problem, but they are extremely expensive and maintaining or upgrading their capabilities is challenging and dangerous. And even high-resolution ground-based instruments must contend with OH lines contaminating the interline region. If ground-based instruments can suppress OH emission, observations at wavelengths longer than 1 micron become far more effective. We discuss the current state and future promise of an OH suppression technology based upon micro-ring resonators lithographically printed onto silicon wafers capable of integration with other on-chip photonic components to facilitate ground-based infrared imaging and/or spectroscopy [1]. These ring resonators will facilitate the observation of the high-redshift universe, including, particularly, supernovae at redshift ~1, extending our ability to probe the effects of dark energy over cosmic time. Secondarily, ring resonators can be used as notch filters to focus on narrow-band observations of positronium, potentially relevant for the detection of sources of dark matter annihilation. We recommend community-wide support for these efforts to push back the cosmic frontier with photonic technologies such as ring resonators.

The Problem: Atmospheric OH Emission Hampers Ground-Based Infrared Astronomy

Observations at near-infrared (NIR) wavelengths (0.9 – 2.5 μm) are crucial for many areas of astronomy. For example, the lowest mass stars and highest mass planets emit most of their light at near-infrared wavelengths, and NIR spectroscopy is essential for classifying such objects. Dusty regions within our own and other galaxies are highly opaque to visible wavelengths, but transparent at long wavelengths due to the λ^{-4} dependence of Rayleigh scattering. Thus, studying the inner regions of the Milky Way, or star-forming regions within other galaxies, often requires NIR spectroscopy. Deep NIR spectroscopy is also necessary to study the high redshift Universe, when the diagnostic visible features are redshifted into the NIR. Measuring star-formation rates during the epoch of peak star-formation, measuring Lyman-α emission during the epoch of reionization, and identifying high redshift-supernovæ would all benefit significantly from NIR spectroscopy (Figure 1).

Unfortunately, deep observations at near infrared wavelengths are currently very challenging due to the bright atmospheric background. The surface brightness of the night sky at an (optically) dark site is thousands of times brighter in the NIR than in the visible. Between 0.9 – 1.8 μm almost all of this background results from the de-excitation of atmospheric OH molecules [2, 3] at an altitude of ≈ 90 km giving rise to an extremely bright emission line spectrum (see Ellis & Bland-Hawthorn [4] and references therein for a review of the NIR background). Not only is this OH line spectrum extremely bright, it is also variable on a time scale of minutes. Subtracting this background from astronomical observations is very inaccurate due to the large Poissonian and systematic noise [5]. Solving the difficulty of the NIR night sky background is a long standing problem in astronomy.

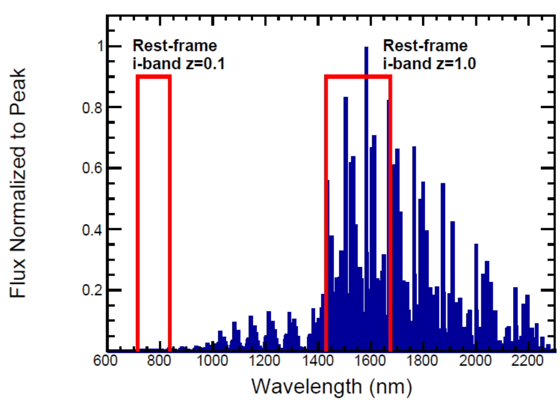
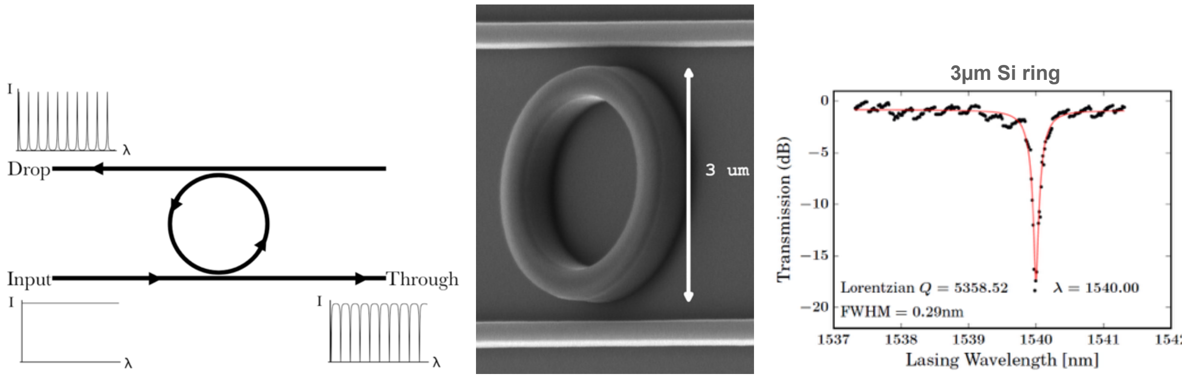


Figure 1: Nearby (z~0) supernovae observable in visible wavelengths (left red outline) would be observable only in the infrared (right red outline) if they were more distant (z~1). Such supernova observations are subject to crippling contamination from the OH emission spectrum (blue lines).

The Solution: Photonic Technologies that Suppress OH Emission

Fortunately, photonic technologies allow for this atmospheric emission to be suppressed, leaving the astrophysical signal much stronger relative to the remaining background [6]. Ring resonators are small (micron-scale) rings lithographically printed on silicon wafers; when broad-spectrum light is fed through a waveguide adjacent to a ring resonator, a notch filter spectrum is created at the "through" port, while a frequency comb spectrum is sent to the "drop" port. Light from a telescope can be fed into such a photonic-integrated circuit, significantly suppressing the OH emission while leaving the majority of the source emission unaffected (Figure 2). Theoretical calculations show that, with a handful of the brightest OH lines suppressed by 20 to 40 dB, signal-to-noise can be increased by a factor of 5 or more in the J and H bands [1].



Left panel: schematic diagram of a simple ring resonator showing the input, through and drop ports and a sketch of the spectrum at each port. Middle panel: SEM image of one of our prototype silicon-based ring resonators with a through port and drop port, manufactured at the Center for Nanoscale Materials at Argonne National Laboratory. Right panel: Transmission plot showing >15dB of suppression in a very narrow wavelength range when light is passed through a waveguide-ring resonator system.

The Current State of Ring Resonators for OH Suppression

Six criteria must be met for this technology to be considered suitable for use in regular observations: 1) Free Spectral Range > 30nm, 2) FWHM of wavelength suppression < 0.4nm, 3) Significant polarization-independence of transmitted light, 4) suppression depth > 20dB, 5) Suppression wavelengths matched (to within a few Å) of at least five of the most prominent OH lines, and 6) Sufficient end-to-end transmission such that the S/N improvement from OH suppression is maintained.

In the last several years of laboratory and on-sky testing, we have achieved the first five of these criteria using our relatively portable (table-top) OH suppression system. In that time, we have also determined that one of the most significant difficulties in realizing this technology is signal loss at the interfaces between fibers (necessary for output from a telescope focal plane and input to a detector) and the photonic waveguides, making the sixth criterion particularly difficult to meet. Through previous testing, we have determined that tapered input/output fibers butt-coupled to the silicon wafer are the method for injecting light into the waveguide with the highest transmission thus far. With a final system in place, we will perform on-sky tests in late 2020 as proof of the capability of this technology, prior to moving from a prototype to a functional instrument. We recommend community-wide support for these efforts, as well as parallel efforts from independent research groups.

Further Applications of Ring Resonators to Cosmic Frontier Observations

While our primary application of photonic ring-resonator technology to the cosmic frontier involves astrophysical probes of dark energy such as supernovae, the filtering capacity of ring resonators can also be used to select narrow wavelength ranges for observation rather than suppression. Reversing the role of the "drop" port and "through" port, narrow-band emission signals from, for example, e+e- (positronium) annihilation provide insight into the physical processes occurring within the inner regions of the Milky Way, with much greater resolution than that provided by gamma-ray telescopes [7]. Narrow-band observations of positronium facilitated by photonic-enhanced telescopes may provide a unique window into the particle physics of dark matter annihilation, or the general relativistic regime around the supermassive black hole at the center of our Galaxy. Given the current interest in positronium in the particle physics community -- and especially the discrepancy between measurements and theoretical predictions [8] – cosmic probes of positronium are especially timely.

References:

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