Deep broad-band infrared nulling using a single-mode fiber beam combiner and baseline rotation

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ABSTRACT

The basic advantage of single-mode fibers for deep nulling applications resides in their spatial filtering ability, and has now long been known. However, and as suggested more recently, a single-mode fiber can also be used for direct coherent recombination of spatially separated beams, i.e. in a "multi-axial" nulling scheme. After the first successful demonstration of deep (<2e-6) visible LASER nulls using this technique (Haguenauer & Serabyn, Applied Optics 2006), we decided to work on an infrared extension for ground based astronomical observations, e.g. using two or more off-axis sub-apertures of a large ground based telescope. In preparation for such a system, we built and tested a laboratory infrared fiber nuller working in a wavelength regime where atmospheric turbulence can be efficiently corrected, over a pass band (~1.5 to 1.8 micron) broad enough to provide reasonable sensitivity. In addition, since no snapshot images are readily accessible with a (single) fiber nuller, we also tested baseline rotation as an approach to detect off-axis companions while keeping a central null. This modulation technique is identical to the baseline rotation envisioned for the TPF-I space mission. Within this context, we report here on early laboratory results showing deep stable ***broad-band dual polarization infrared nulls < 5e-4*** (currently limited by detector noise), and visible ***LASER nulls better than 3e-4 over a 360 degree rotation of the baseline***. While further work will take place in the laboratory to achieve deeper stable broad-band nulls and test off-axis sources detection through rotation, the emphasis will be put on bringing such a system to a telescope as soon as possible. Detection capability at the 500:1 contrast ratio in the K band (~2.2 microns) seem readily accessible within 50-100 mas of the optical axis, even with a first generation system mounted on a >5m AO equipped telescope such as the Palomar Hale 200 inch, the Keck, Subaru or Gemini telescopes.

Keywords: Nulling, Interferometry, Infrared, High Contrast Imaging

1. PRINCIPLE

Figure 1 shows the optical set-up used for the fiber nuller. It is difficult to conceive a more simple way to recombine and null two beams. The light beam from a point source is collimated, and two sub-apertures are defined through a mask. In the case of monochromatic light, the two beams defined are then delayed with respect to each other by $\lambda/2$ using a split mirror, before being focused and injected into a single-mode fiber. This can be seen as a simple Young's slits experiment.

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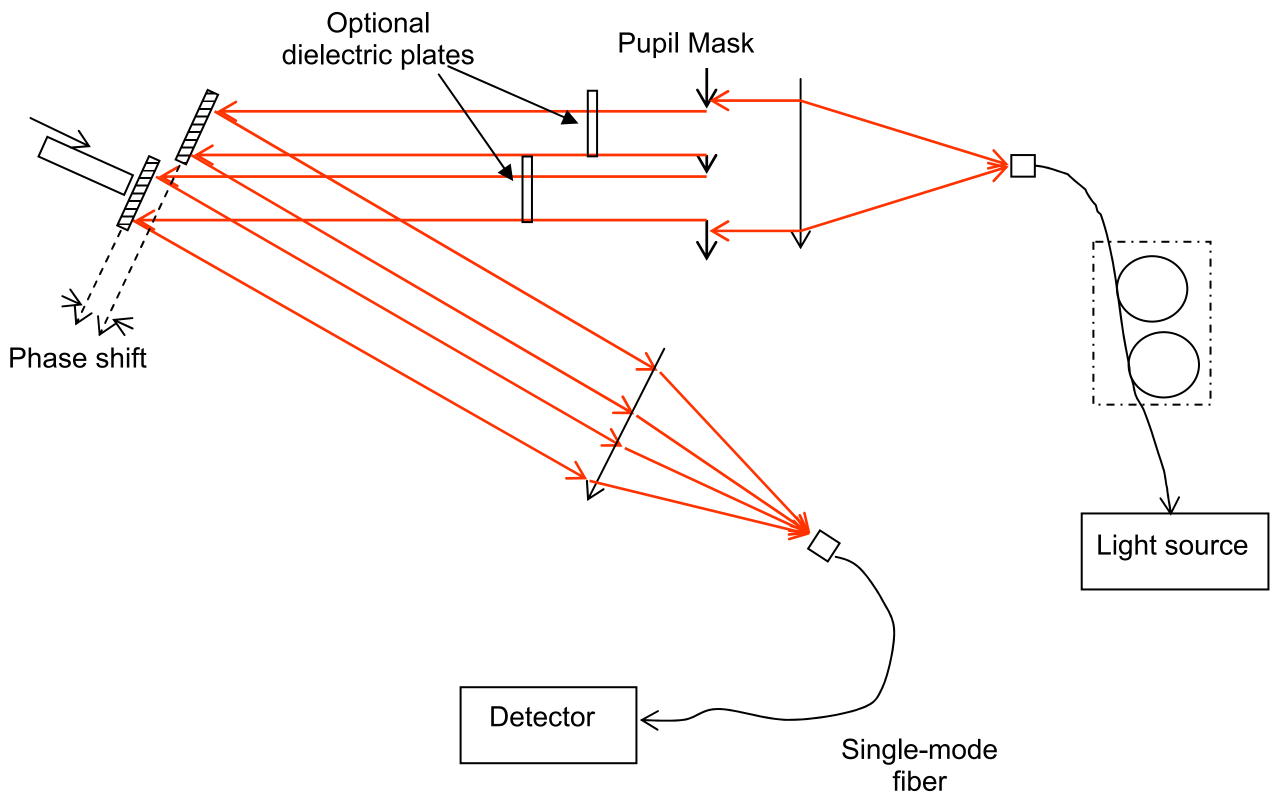

Fig. 1: Fiber nuller set-up. The "optional" dielectric plates are only used in the broad-band infrared experiment (see text for details). The pupil mask can be rotated around the optical axis.

On the fiber's head, where the beams are focused, the electric field resulting from the interferences between the two beams goes through zero and changes sign when crossing the optical axis. The electric field is an odd (or anti-symmetric) function of the distance to the optical axis, and then couples totally destructively with the fundamental (symmetric) mode of the fiber.

The case of a polychromatic source is identical, but for the phase shifting device. The π phase shift can no longer be created by a simple split-mirror optical path difference (opd). A quasi achromatic π phase shift -over the band-pass of interest- is produced using two dielectric plates of different thicknesses in conjunction with some opd in air provided by the split mirror. Theoretical nulls of the order of 10^{-6} or better can be achieved by using a single commercial infrared glass over the full H (~1.5 to 1.8 microns) or K (~2.0 to 2.4 microns) astronomical windows. The set-up represented in figure 1 already demonstrated visible LASER nulls at the 1.1e-6 level, validating the approach of fiber nulling in the monochromatic case (Haguenauer and Serabyn, 2006).

2. FROM A FIXED HE-NE SET-UP TO AN IR BROAD-BAND ROTATING NULLER

3.

For proper operation on astronomical telescopes, two essential upgrades are now necessary:

2.1. Fast baseline modulation

This was tested using the visible LASER set-up. The baseline modulation was simply provided by rotating a pupil mask with two d=5mm diameter holes which define the beams to be nulled (figure 1). Modulation can then be done at reasonably high frequencies in the 0.01 to 1Hz range. Initial tests using slow opd control and slow rotation (100s period) already allowed to obtain consistent LASER nulls better than 3e-4 (fig. 2) over 360 degrees rotation (minus the dead zones where the sub-apertures intercept the split-mirror axis). For a telescope set-up, apparent baseline rotation may preferably be provided using a rotating "K mirror" located upstream of a steady mask.

As part of the fast modulation demonstration, it is also planned to simulate a close-by dimmer off-axis source using a second fainter visible laser launched into the experiment at a small angle (< λ/d). This will allow to assess the ability to detect close companions with the fiber nuller, and test algorithms for signal extraction on real astronomical data from rotating nulling interferometers, a most interesting prospect in preparation for the TPF-I / DARWIN missions.

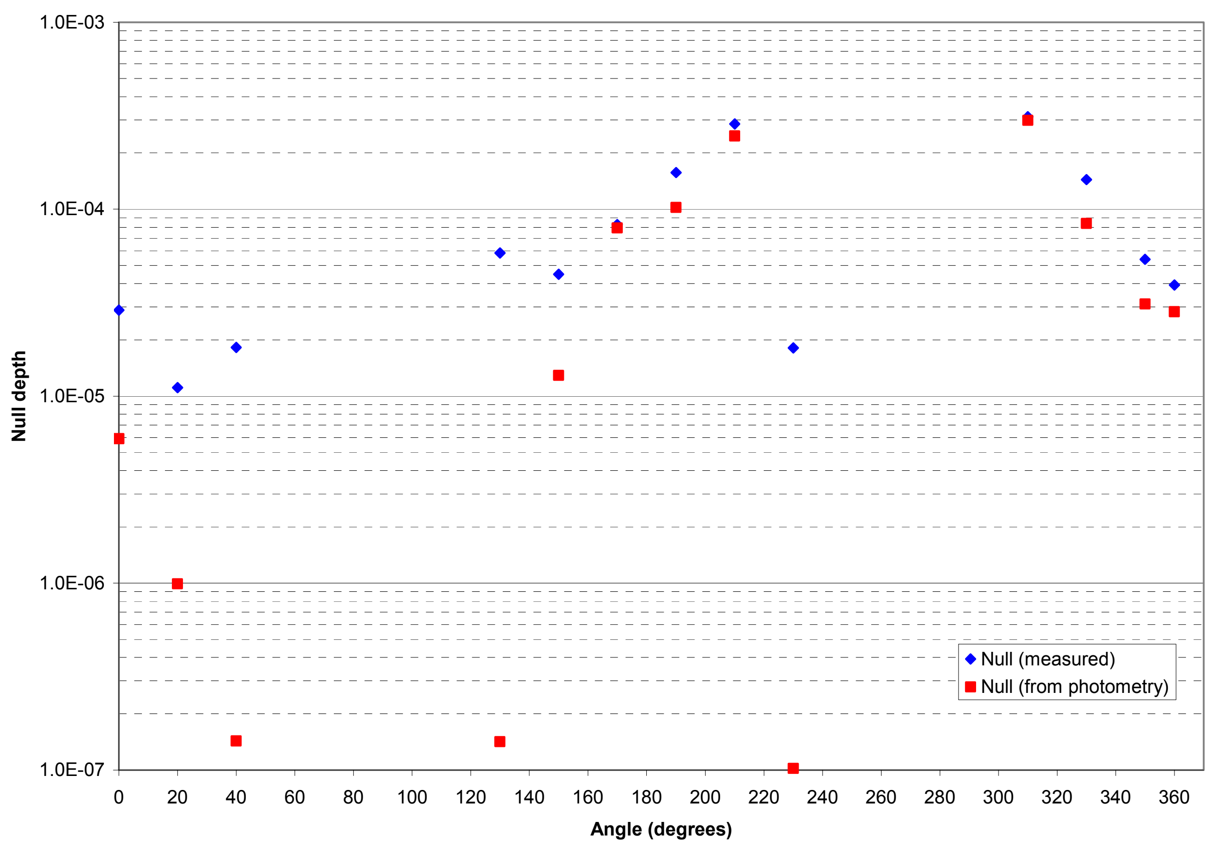

Fig. 2: Blue diamonds: null depth obtained over rotation of the pupil mask, using HeNe LASER light. The "dead zones" visible between ~ 40 and 120 degrees, and 230 and 310 degrees rotation correspond to the angle positions for which the individual beams intercept the vertical "dead" region of the split mirror (fig.1). A slow optical path stabilization is applied. Worse nulls are at the 3e-4 level and entirely limited by intensity imbalance (red squares): as the mask rotates around the optical axis, the beams to be interfered go off or through different parts of the split mirror and final injection lens. Since these optics are not perfect (typically $\lambda_{vis}/20$ rms), a slight tip-tilt is created over the rotation, and causes the injected signal strength to vary, casing the nulls to deteriorate. Note that this effect and its impact on null depth are considerably reduced in the near infrared.

2.2. Broad-band near infrared nulling

We used two dielectric plates with a differential thickness optimized to provide the best broad-band null depth over the whole atmospheric H-band (~1.5-1.8 microns, theoretical limit <1e-6). A 1100K white light source coupled to an IR single-mode silicate fiber is used as a light source. A similar fiber is used at the output. The beam exiting the output fiber's head is then re-collimated, modulated via a mechanical chopper (~100Hz) and refocused onto a commercial single-pixel InSb detector. The output of the detector is then read via a lock-in amplifier performing a synchronous detection over a tunable timescale (>10ms). The current performance is illustrated in Figure 3. It is presently limited by detector noise, but while light dual polarization null levels are already clearly below 5e-4.

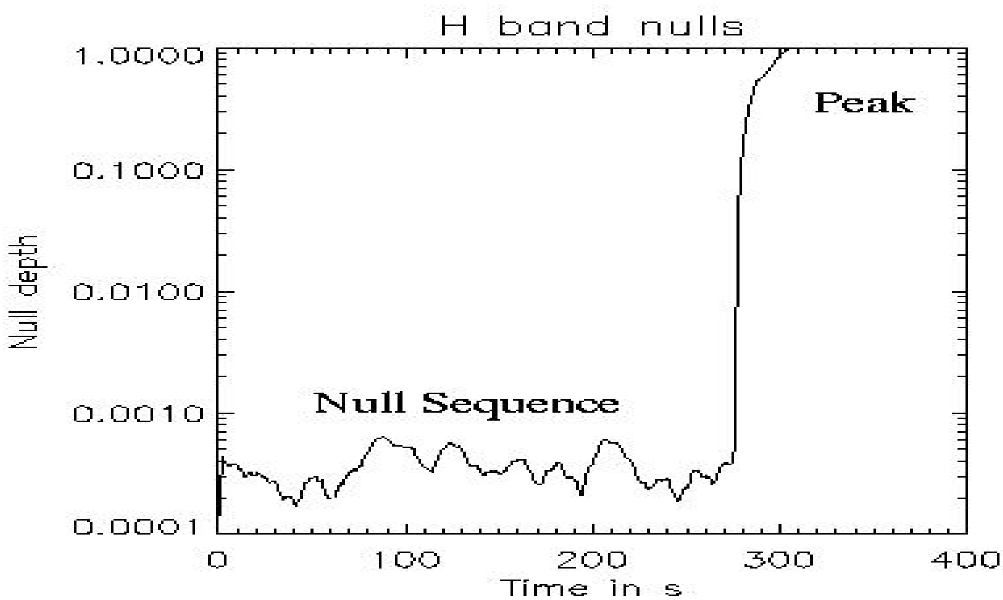

Figure 3: Typical null sequence (10s moving average) obtained in the infrared in the H band (~1.5 to 1.8 micron). Null depth and stability are currently limited by detector noise. The average null over the sequence is 3.5e-4, and the best 10s average null is 2e-4.

4. PERSPECTIVES ON GROUND BASED TELESCOPES

As an initial on-sky test, we plan to use the infrared fiber nuller in a narrow band-pass (typically ~ 100 nm wide) located inside the K atmospheric window. This allows to use the simple set-up of figure1, *including fast modulation with a rotating pupil mask.* With the limited band-pass there is no need for dielectric plates to obtain good broad-band nulls. As an example, restricting the wavelengths to the [2.1 – 2.2 microns] region, dispersion limited nulls are still 2200:1. Our first case analysis is based on two 1.5m sub-apertures separated by b=3.5m on a >5m telescope with 200 nm rms residual wavefront error. Such a system provides for a spatial resolution (first constructive peak at $\lambda/2b$) of 63 mas, with a half power point at 32 mas. Simulations as presented in figure 3 suggest that for stars brighter than mK=3, 10^{-3} transient (10 ms reads) nulls can be reliably measured over a 100 nm wide band-pass. (The intensity coupled from each sub-aperture is also measured at this rate for proper calibration of the null depth). Figures 4a and 4c show the expected signals from mK=3 stars with 500 times dimmer companions at respective distances of 40mas and 200 mas. Note that a mean opd of 100 nm rms (consistent with the overall aperture wavefront figure after AO correction) is assumed between the 2 sub-apertures, translating into a mean null level of only 50:1. A significantly better null performance would be obtained on a telescope equipped with extreme AO, and/ or using an additional fringe tracker to stabilize the opd between the 2 sub-apertures, an attractive prospect with large sub-apertures of a meter or more in diameter. Differential imaging techniques could also be used between 2 channels of the K band in order to further decrease the impact of atmospheric effects on faint neighbor detections. The final fiber nuller performance using extreme AO, fast fringe tracking, several sub-apertures, differential imaging and state of the art cameras on >8m telescopes remains to be properly estimated at this point.

There are essentially 3 types of science targets for the fiber nuller: spectroscopic binaries, young sub-stellar companions, and circumstellar disks. In each case, the possibility of achieving magnitude differences of ~7-8 at only 50 mas from the optical axis opens up a whole new class of astronomical investigation / characterization. It clearly shows the specificity of the rotating sub-aperture fiber nuller, which can be considered as a natural complement to a coronagraph. It starts being sensitive precisely where a regular coronagraph can not observe anymore, i.e inside 2-3 λ/D. A large field of view is not needed for nearby faint neighbors detections, and the fiber nuller is finely tuned for this application.

5. CONCLUSIONS

We have successfully achieved deep (<5e-4) laboratory nulling of un-polarized white light over a broad infrared band pass using a single-mode fiber for beam combination, and dielectric plates for quasi achromatic phase shifting. Simultaneously, visible LASER nulls were shown to be consistently deeper than 3e-4 over a full baseline rotation, using slow optical path stabilization, and no tip-tilt correction. Even better performance is expected in the infrared, where the impact of optics imperfections is strongly reduced.

Future developments will first concentrate on demonstrating stable broad-band infrared laboratory nulls consistently below the 1e-4 level over a 360 degree rotation. At this point an initial K-band fiber nulling experiment – with a rotating mask, a split mirror, a single-pixel detector and no active correction of residual piston between sub-apertures- will be deployed at the Palomar 200 inch telescope. This will allow to assess the detectability of binary pairs with contrast ratios of a few 100:1 and separations smaller than 100 mas with such a system.

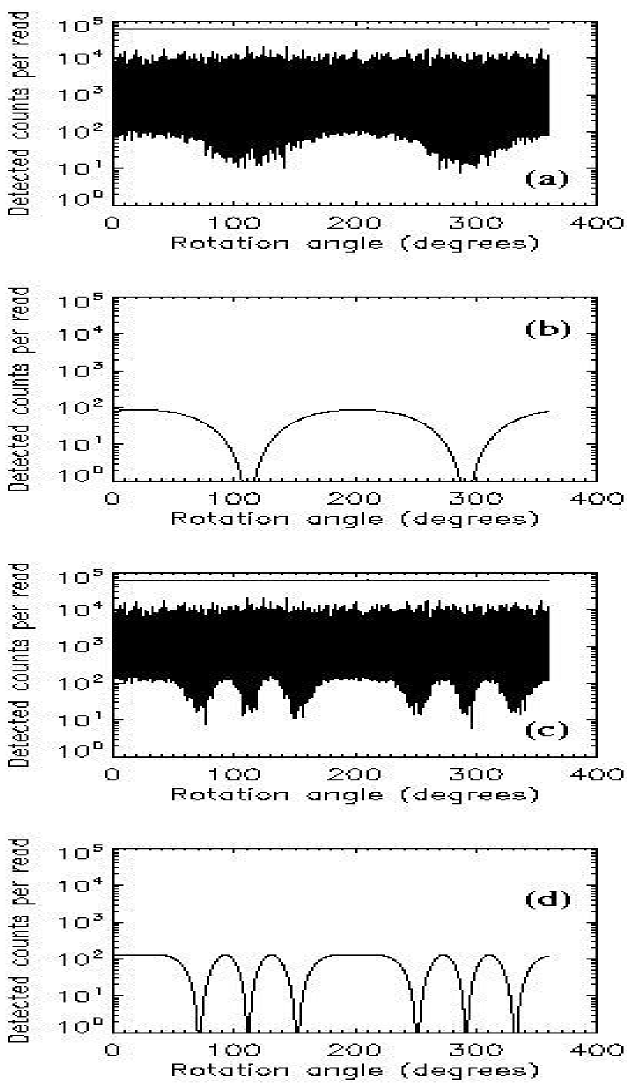

Figure 4: Expected performance on the Palomar 200 inch telescope, working in the K band. Individual points represent the signal measured for each baseline orientation, over 60 successive rotation cycles, each turn taking 5 seconds. The read-out time is 10 ms , i.e. 500 reads per rotation. a) Null signal obtained from a magnitude 3 star with a 500 times dimmer companion 40mas away. All noise sources included. Top horizontal line at ~10^5 counts level indicates the

constructive signal. b) Expected signal from the companion alone, no noise, no background. c) and d): Same as (a) and (b) respectively, but for a companion 200 mas away.

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