Current progress on TPFI nulling architectures at Jet Propulsion Laboratory

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ABSTRACT

Infrared interferometric nulling is a promising technology for exoplanet detection. Nulling research for the Terrestrial Planet Finder Interferometer has been exploring a variety of interferometer architectures at the Jet Propulsion Laboratory (JPL). Three architectures have been identified as having promise for achieving deeper broadband IR null depths. Previous nulling research concentrated on layouts using dispersive elements to achieve a quasi-achromatic phaseshift across the passband. However, use of a single glass for the dispersive phase shift method inherently limits the nulling bandwidth. JPL is researching use of multiple glass types to increase null depth and bandwidth. In order to pursue nulls over much broader wavelength regions, nondispersive interferometer architectures can be employed. Toward this end, JPL has been researching two reflective architectures as nulling interferometers. The key enabling technology for this and other nondispersive field flip architectures is single mode spatial filtering devices. We have obtained results with both pinhole spatial filtering and single mode fibers.

Keywords: exoplanet detection, nulling interferometry, terrestrial planet finder, interferometry architecture, achromatic phase shift

1. INTRODUCTION

As one of the primary enabling technologies for exoplanet detection, interferometric nulling is a continuing area of focus at JPL. Previous testbeds have produced null depths of better than 10^6 for a laser[1] and 10^4 for a broadband infrared source[2]. The results reported in this paper are a continuing step along the path toward the ultimate broadband nulling requirements for the Terrestrial Planet Finder mission. Each new nulling milestone exposes challenges. Earlier broadband nulling was done using the quasi-achromatic phase shift characteristic of dispersive phase plates. Deeper nulling with dispersive elements cannot be done with a single glass type. This leads to a more complex design using multiple glasses for the dispersive phase plates.

Alternatively, a truly achromatic phase shift can be implemented in a fully reflective system. In this case, the 180 degree phase shift is achieved through a geometric field flip using mirrors. We are pursuing two implementations of this: a through focus layout and a periscope layout. However, due to the pupil inversion in these architectures, the source is required to be spatially coherent. In order to obtain the necessary coherence, single mode optical fibers are being developed for the waveband of interest.

In addition, in order to measure null depths of 10^5 or deeper requires a detector dynamic range of at least the same order of magnitude. This introduces the need for brighter broadband IR sources. To this end, we have developed an argon arc source which is significantly brighter than previous sources.

2. INTERFEROMETRIC NULLING ARCHITECTURES

At JPL we are pursuing three architectures to achieve deep interferometric nulls in the 8 – 12 micron region. The first testbed architecture is a continuation of the dispersive system used to achieve 10^4 null depths previously. The other two testbeds employ different geometries to achieve fully reflective phase delays.

2.1 Dual glass phase plate testbed

For a single wavelength, the nulling condition can be accomplished by the introduction of a path delay difference between the two arms that results in a phase change of π. The phase change at a single wavelength due to a path delay is given by $\phi = 2\pi\, \Delta x/\lambda_0$. As the spectrum is broadened around this center wavelength, the shorter wavelengths will pick up a proportionally larger phase change, and longer wavelengths will pick up less than π phase change. The phase change is given as $\phi(\lambda) = \pi\,(\lambda_0/\lambda)$. Starting from this initial condition, it's possible to add an air delay in one arm while subtracting an equivalent amount of dielectric such that the phase at the center wavelength is still near π, while the net phase for wavelengths both shorter and longer have improved. This technique was initially proposed by Morgan, et.al.[3] and was demonstrated in the visible. We have applied it to the mid-IR using a method they also proposed.

All previously reported broadband infrared nulling results at JPL have been obtained using the dispersive phase plate method. The differential path length is introduced between the interferometer arms by placing slightly different thicknesses of zinc selenide (ZnSe) plates in each arm. This allows for deep nulling over a limited waveband. For example, a 30% bandwidth centered at 10 microns will allow a maximum null depth of $3\text{x}10^4$. In order to achieve deeper nulls and/or broader bandwidths, we must use two types of glass. A combination of ZnSe and zinc sulfide (ZnS) will allow 10^8 nulling over a similar 30% bandwidth.

The interferometer layout is shown in Figure 1. Near net thickness plates of ZnSe and ZnS are placed in each beam. The plates are then rotated to achieve the desired differential glass thickness for each glass type. The differential air thickness is also adjusted to maintain the destructive null fringe by translating a fold mirror.

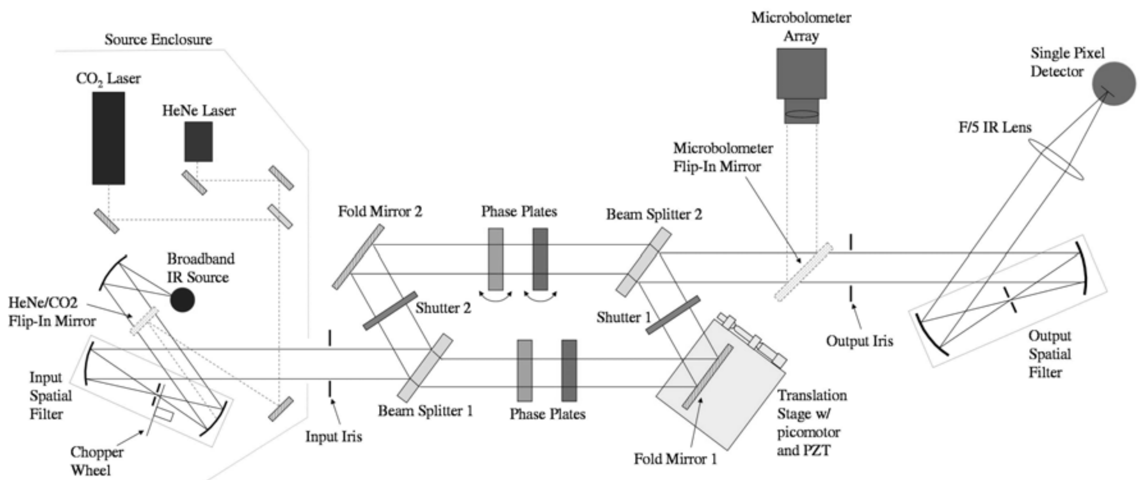

Figure 1: Block layout of dual glass phase plate nulling interferometer.

2.2 Through focus testbed

Whereas the phase-plate technique accomplishes a net phase change by introducing compensating dispersions, the through-focus field flip introduces an achromatic π phase change from diffraction[4]. By putting the light through focus, the beam acquires an achromatic phase change. This technique was first proposed and demonstrated by Jean Gay, et.al.[5] with an instrument having the clever acronym CIA[6,7] (coronagraphe interferential achromatique). The architecture is shown in Figure 2.

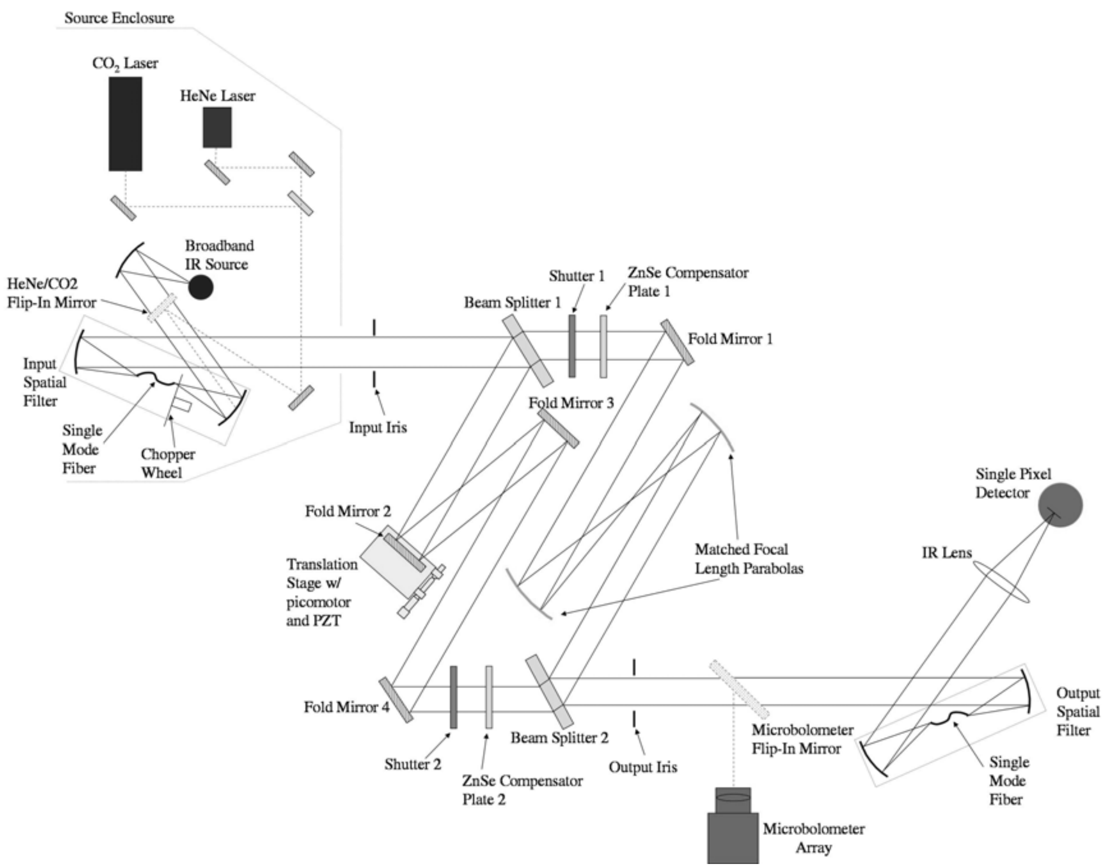

Figure 2: Block layout of through focus nulling interferometer.

This method, by its very nature, is broadband. In particular, if it were possible to develop a beamsplitter that covers the full TPF bandpass, then nulling could be done with a single device. However, producing a null even over a restricted portion of the band would give us great confidence in employing this method to cover the full band since most of the physics is captured by a handful of optics.

Polarization is a known problem with this method. We use the parabolas in an off-axis configuration to give an un-obscured pupil. The angle of incidence varies across the pupil and creates a pupil-dependent change in the s-p polarization phase delay. These effects can be balanced, on average, by the angle of incidence on the flat mirrors of the other arm of the interferometer. It can also be minimized by a judicious selection of focal lengths and off-axis distances. But, it can never be eliminated.

The surface figure errors for powered surfaces can never be made to the same level as a flat surface. That and the alignment of these elements make it harder than a system completely composed of planar optics.

2.3 Periscope testbed

In this architecture, the field flip is created by an inversion of one pupil relative to the other. This method has its roots in the rotational shearing interferometer[8,9,10,11]. The original RSI showed great promise for nulling owing to its attractive polarization balancing properties, use of flat surfaces and simplicity. Limitations of the early RSI system have been handled by making the periscope layout fully symmetric. As with the through focus system, two phase compensator plates are used to account for dispersion due to beamsplitter thickness mismatch. Due to the geometric nature of the field flip, this architecture is also intrinsically achromatic. Thus a demonstration of this method over a portion of the 7-17 um band for TPF would give great confidence that the other portions of the band could also be nulled with perhaps only a change in the beamsplitter and compensator substrate.

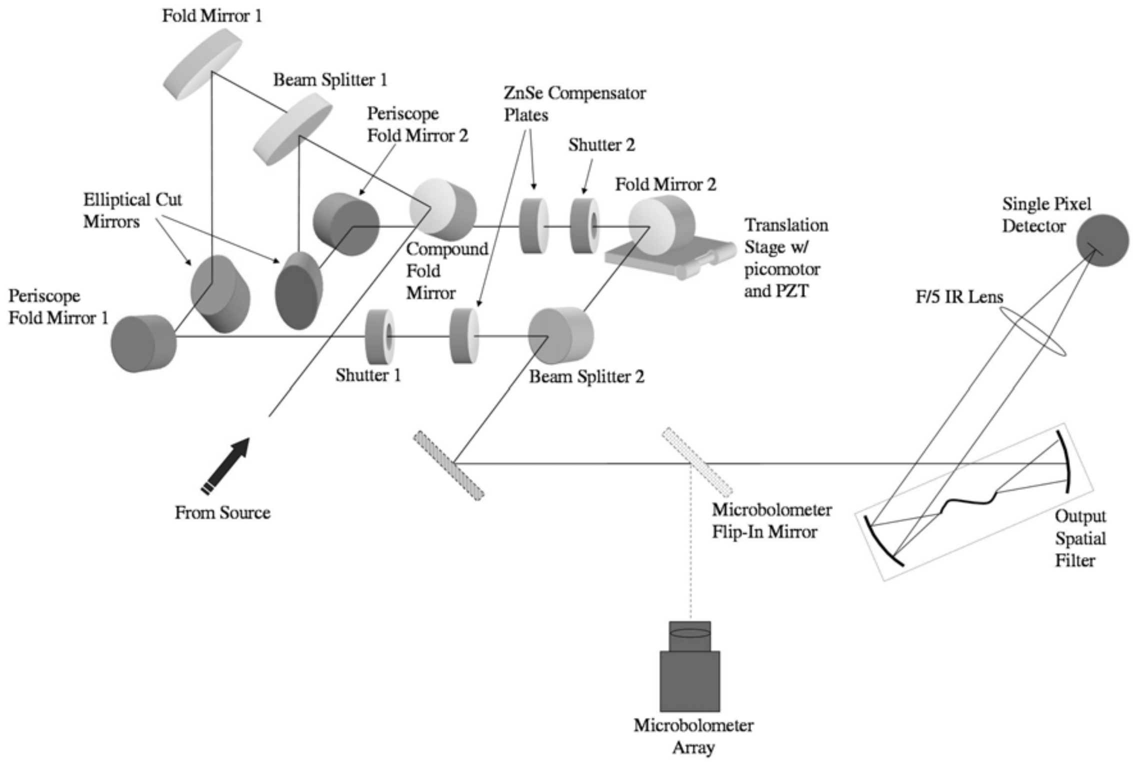

Figure 3: Block layout of periscope nulling interferometer.

We have begun our laboratory testing with discrete components for the periscope elements that form the heart of this nulling arrangement. These are in the process of being replaced with a single monolithic nulling periscope. Because this element is a single component, it will keep the periscope permanently aligned. The monolith has been constructed via optical contacting of four separate prisms to a base plate. All the mirror surfaces were coated with bare gold simultaneously to insure the most homogeneous reflective properties between them. This single monolithic periscope greatly simplifies the alignment since one only has to guarantee the shear and co-linearity of the two input beams, and matched angle-of-incidence on the output.

Every surface in this configuration is planar, and is therefore easily fabricated to high quality. Perhaps the greatest difficulty with this method is that the input and output beams are non-coplanar. This could perhaps be mitigated with the addition of a couple of extra mirrors, but a system with the minimum number of surfaces is preferred.

3. ENABLING TECHNOLOGIES

In order to measure very deep interferometric nulls, we need a system dynamic range greater than the desired null depth. One basic method to achieve this is to increase source brightness. At JPL we have developed an argon arc source which produces roughly 8 times more light in the waveband of interest than the previously used ceramic thermal source. This arc source is modeled after one developed at NIST which behaved as a 5000 – 10,000 K blackbody in the thermal infrared region[12]. The details of this arc source are available in another paper[13].

In addition to the dynamic range issues, the through focus and periscope interferometers introduce a need for a spatially coherent source. Since broadband sources lack spatial coherence, single mode fibers for the 8 – 12 micron waveband are necessary. These have been developed by NRL for use at JPL[14].

4. RESULTS

The following results reflect the current progress on two of the three testbeds. We have measured the deepest nulls using the phase plate testbed. This is primarily due to the larger dynamic range of that system. However, we have achieved promising results on the through focus architecture as well.

4.1 Dispersive nulling results

Our current best optimization of the dual glass phase plate architecture yielded null depths on the order of 10^5.

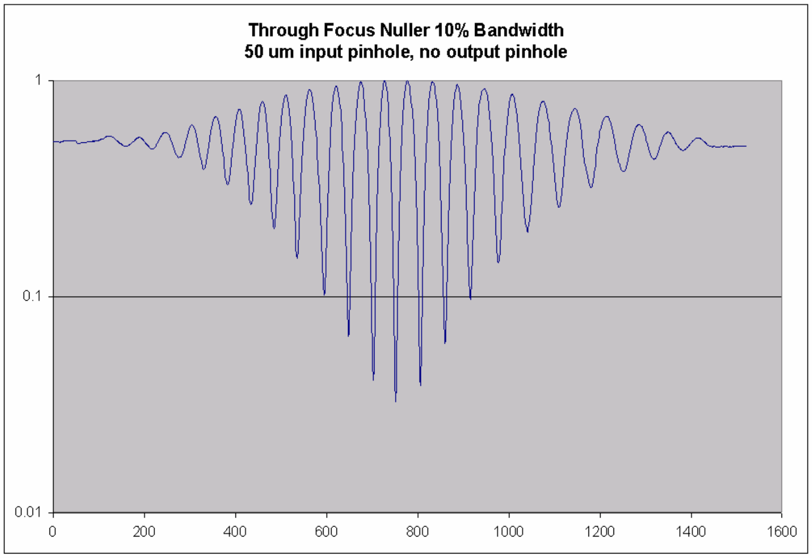

Figure 4: Current nulling results for dual glass phase plate nuller.

4.2 Reflective nulling results

Although the dynamic range of the through focus architecture limits our ability to measure deep nulls, we were able to achieve null depths within a factor of 2 of the noise limit. At this level, the null depth is approximately $5x10^4$.

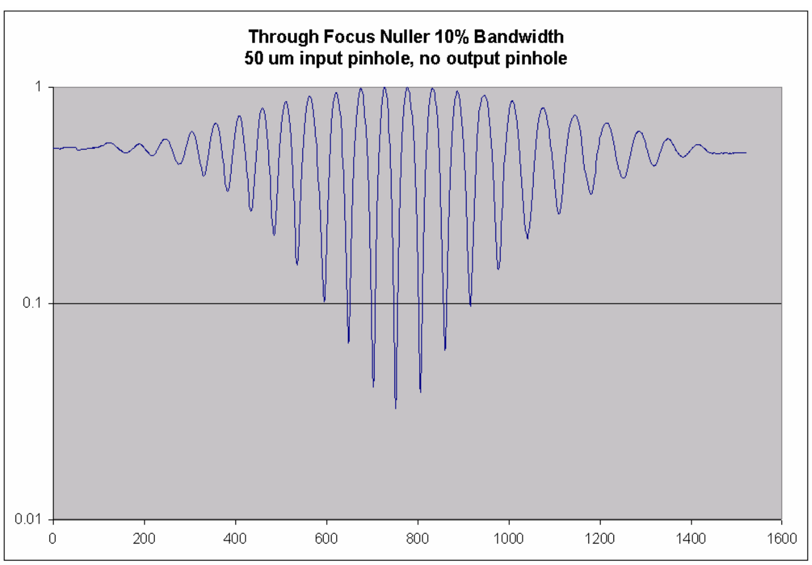

Figure 5: Current nulling results for through focus nuller.

5. CONCLUSION

Ongoing research on deep infrared interferometric nulling is continuing on pace. We are pursuing deep nulls on several interferometer architectures while also developing the technologies required to reach the next level.

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