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Event: SPIE Optical Engineering + Applications, 2013, San Diego, California, United States

Adaptive Phase Mask Coronagraph with Amplitude and Phase Modulation for High Dynamic Range Synchronous Detection: APM^2 Coronagraph

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ABSTRACT

We present a new Adaptive Phase Mask (APM) coronagraph design enabling Amplitude and Phase Modulation control (APM). The Adaptive Phase mask coronagraph is a technique proposed to provide both high dynamic and high angular resolution imaging of faint sources around bright objects. Discriminating faint sources from static speckles is a challenging problem. Our new system is based on synchronous demodulation that allows high dynamic range detection of a faint target immersed in a background. The APM^2 uses the coherence of speckles to discriminate them from proper companions, using the mask itself as the electric field modulator. Synchronous detection in the radio frequency range is used to side-step the effect of atmospheric turbulence and enable the detection of low amplitude signals. The APM^2 concept offers high dynamic range detection and provides a time- and cost-effective method to quantify the probability of presence of a faint object close to the central star.

Keywords: High-contrast imaging, coronagraphy, polarization, high angular resolution, phase mask, adaptive optics, synchronous detection

1. INTRODUCTION

High contrast imaging of extra-solar planets and close environments of bright astrophysical objects in general, such as stars or active galactic nuclei, is a challenging task. Coronagraphy is now recognized as one of the must-have tools to help take on this task. Tremendous progress has been accomplished this past two decades focusing mostly on improving coronagraph concepts and technologies (Roddier, Rouan, Guyon, Mawet, N'diaye and others), observation strategies (Marois et al. 2006) and also post processing techniques (lafrenière et al. 2007, Soummer et al. 2012). For ground-based observations, next generation of adaptive optics systems (Extreme-AO) was developed to provide high-Strehl regime for small inner working angle (IWA) observations. Accessing small IWA (~ 1−2λ/d) is considered as an edge because it provides substantial scientific and technical advantages (Mawet et al. 2012b). For instance, it opens up new discovery spaces in the inner regions of stellar systems, while allowing reaching out to more distant systems in young stellar associations (Mawet et al. 2012a). The principal drawbacks are the operational complexity and overheads and the inconsistence in performances with respect to atmospheric conditions, calibrations and the overall system health. In addition, the data flow associated to imaging campaigns often prevents final detection limits to be computed in a short enough time when strategic real time decisions could optimize telescope time and the scientific outcome.

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Techniques and Instrumentation for Detection of Exoplanets VI, edited by Stuart Shaklan, Proc. of SPIE Vol. 8864, 88640J · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2026211

Our original approach presented in this paper aims at providing a quick tool to quantify the probability of presence of a stellar companion in a short observation time. Such a vetting technique will allow deeper coronagraphic observations to focus on “interesting” targets, all with the goal of optimizing operational efficiency. The instrument concept is based on the synchronous demodulation technique. The theory of detection of amplitude modulation (AM) signals in noise was developed first by Rice, Van Vleck, Middleton and others (1945), and will not be detailed here. The efficiency of this technique increased after the technological developments of microelectronics, signal processing facilities in the radio frequencies range and was used as a means of providing target position information to tracking systems (Lowell 1961, Carpenter 1963). The problematic of detection and tracking of a faint-hot thermal source in a thermal background is however quite different from the detection of a stellar companion immersed in a field full of static speckles and dynamic AO correction residuals.

Each static speckle induces AM signal and behaves as a possible companion. However, the coherence of the speckle with the central star enables to discriminate it with a pure phase modulation (PM). The PM is performed using the geometrical phase (Pancharatnam 1956; Berry 1987); the PM is realized by rotation of the polarization exploiting the properties of twisted nematic or cholesteric liquid crystals with a segmented Adaptive Phase Mask (Bourget et al. 2012). The amplitude and phase modulations (APM) performed by the segmented Adaptive Phase Mask (APM) are at the core of the APM^2 instrument concept, enabling high dynamic range synchronous detection. This time- and cost-effective technique could greatly optimize the observation strategy with classical extreme-AO coronagraphs by vetting targets in advance (binaries), but would also enable large-scale surveys of stellar populations, looking for binarity statistics, which is a scientifically rich niche still largely unexploited.

2. HIGH DYNAMIC RANGE SYNCHRONOUS DETECTION

Looking at the output focal plane of a phase coronagraph, after an Adaptive Optics (AO) correction, a limited field of view centered on the star will see the following:

- The diffraction residuals of the destructive interference performed by the coronagraph on the star.
- A variable background due to the residuals of the AO correction changing the shape of the energy distribution of the Point Spread Function (PSF).
- Static speckles.
- Companion(s).

However, the integrated flux over the field of view as measured, e.g., by a single-pixel detector will remain mostly constant by conservation of energy.

2.1 Amplitude modulation

The amplitude modulation (AM) is widely used as a means of providing target position information to tracking systems. The AM modulation based on the spinning reticules techniques uses the synchronous demodulation allowing detection and tracking of a faint target immersed in a thermal background with a dynamic up to 10^6 (Rice, 1945). In our concept, the amplitude modulation is done at the output focus of a coronagraph. The first coronagraphic stage is only used to decrease the photon noise, and amplify the relative speckle amplitude. The AM is done as in any twisted-nematic amplitude modulator using a segmented Adaptive Phase Mask. A polarized beam splitter (PBS) feeds the APM with a linear polarization (the other polarization feeds the viewer detector, see Figure 1). The segmented APM is made of two optical windows where transparent electrodes are distributed in a pie-chart pattern; liquid crystals are sandwiched in-between. The voltage applied on the pie charts electrodes is controlled to modulate the orientation of the linear polarization state incident on the second polarized beam splitter to perform the modulation of transmission. The modulations of amplitudes detected by the two avalanche photodiodes (APD) are phase shifted thanks to the second PBS.

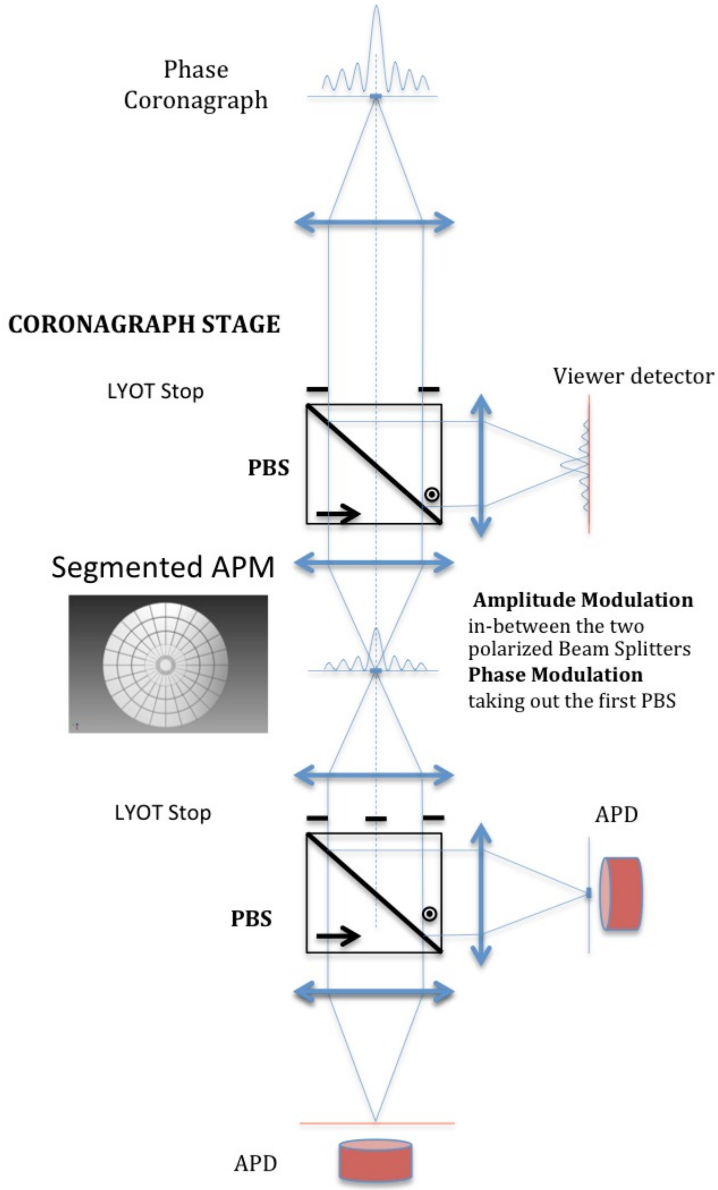

Figure 1. The figure shows the Amplitude Modulation setup using the first PBS. The first PBS is extracted from the optical path to perform the Phase Modulation. The detection of the static or quasi-static speckles can also be done using the viewer detector instead of the Amplitude Modulation at the cost of a more complex analysis chain. In that case the PBS is replaced by a beam splitter for a simultaneous Phase Modulation to discriminate the static speckle from the companion. The Phase Modulation is done on the identified speckles.

The segmented APM can modulate the rotation of polarization; when placed between two PBS, the APM can modulate a selected region from zero to full transmission at a carrier frequency ω. The transmission modulation of the APM is performed on pairs of complementary out-of-phase APM segments (blue and red Figure 2) to keep the global flux invariant on the APDs. If a static speckle or companion is present in the blue segments, the modulation of transmission will create an amplitude modulation on the APDs. The flux is almost constant on an APM ring if the star is centered on the coronagraph; a decentering is detected by the complete mapping done on a ring and its effect suppressed by the analysis.

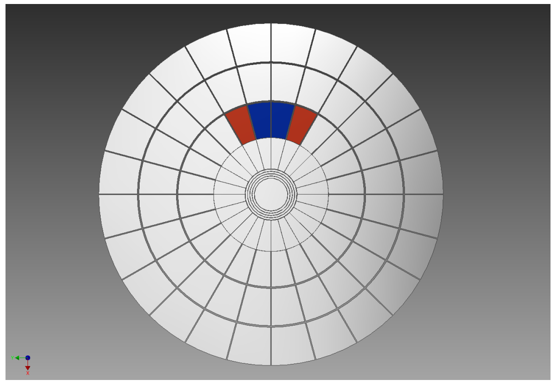

Figure 2. Sine wave modulation of transmission is performed phase shifted on pairs of complementary pie charts (blue and red); a mapping of the complete APM is done exploring all the segments. The presence of an non homogeneity in the flux repartition induced by a companion or a static speckle in the two blue pie charts will creates a modulation of amplitude on the signal received by the APDs.

2.2 Synchronous demodulation

The instrument concept lends itself to an application of synchronous demodulation, which is a way of measuring the component of a signal that is synchronized in frequency and phase with a reference signal. The synchronous demodulation can even reject the noise at the same frequency as the signal of modulation because "noise" will have a random phase, while the demodulator looks for signals with the same frequency and phase as the reference signal. Synchronous detection in the radio frequency range (500 to 1 kHz) is used to side-step the effect of turbulence. This capability also corresponds to the specifications of liquid crystals control of commercial active phase retarder plate.

Without going into details, the efficiency of the synchronous demodulation can be explained as follows. The synchronous demodulation noise limitation depends on the Noise Electronic Power (NEP) of the detection apparatus (APD + amplifier), which is an $Hz^{-1/2}$ function. Therefore, the amplification bandwidth defines the detection capability, and the gain relative to the non-modulated case. For instance, if we single out the frequency of interest by a synchronous detection with a bandwidth as narrow as 1 Hz instead of the ~1MHz bandwidth obtained without synchronous demodulation, the signal to noise ratio is increased by a factor ~1000, and an accurate measurement is therefore possible.

Lock-in amplifiers use a technique known as phase sensitive detection to single out the component of the signal at a specific reference frequency and phase. Noise signal at frequencies other than the reference frequency is rejected and does not affect the measurement. For high precision measurement the lock-in reference frequency must be the same as the signal modulation. More precisely the phase between the two signals cannot change with time; the lock-in reference needs to be phase-locked to the signal one is trying to detect. For that reason, a Phase Lock-in amplifier provides the phase lock-in reference that will feed the APM through a controller to perform the pie chart mapping of the focal plane.
Let us assume that the shifted phase reference signals provided by the Phase lock-in Amplifier equal to: $V_R \sin(\omega t+\theta_R)$ and $V_R \cos(\omega t+\theta_R)$ where ω is the reference frequency and V_R the signal amplitude. The modulation of the transmission of the APM (in the case of the presence of a speckle or companion) will induce a modulation of the photodiodes signal output as follow: $V_1 \sin(\omega t+\theta_1)$ and $V_2 \cos(\omega t+\theta_2)$.
The lock-in amplifier multiplies the signal by the reference signal using a mixer. The mixer generates the product of its inputs as its outputs V_{M1} and V_{M2}. (see Figure 3.)

$$V_{M1} = V_1 V_R \sin(\omega t+\theta_1) \sin(\omega t+\theta_R) = ½ V_1 V_R \cos(\theta_R-\theta_1) + ½ V_1 V_R \sin(2\omega t +\theta_R+\theta_1)$$
$$V_{M2} = V_2 V_R \cos(\omega t+\theta_1) \sin(\omega t+\theta_R) = V_2 V_R \sin(\omega t+\theta_1+\pi/2) \sin(\omega t+\theta_R)$$
$$V_{M2} = ½ V_2 V_R \cos(\theta_R-\theta_1-\pi/2) + ½ V_2 V_R \sin(2\omega t +\theta_R+\theta_1+\pi/2)$$

Since the inputs to the mixer are at *exactly* the same frequency, the first terms in the mixer outputs M1 and M2 is a DC. The second terms are at a high frequency 2ω. This second term can either be magnified by spectrum analysis to detect a possible modulation with high sensitivity, or removed using a low pass filter for the phase sensitive detection.

After filtering we have

$V_{M1} = ½\, V_1\, V_R \cos(\theta_R - \theta_1)$
$V_{M2} = ½\, V_2\, V_R \sin(\theta_R - \theta_1)$

The phase lock-in amplifiers uses also two mixers (with reference inputs π/2 out of phase) to provide a direct determination of all the phase modulation components. These computations are handled by a DSP chip that also can perform simultaneous analysis of symmetries of modulations (due to static speckles or circumstellar disk), spectrum analysis, but also asymmetries dues to decentering of the coronagraph. A multiplexing in frequency should allow simultaneous analysis of each ring of the APM.

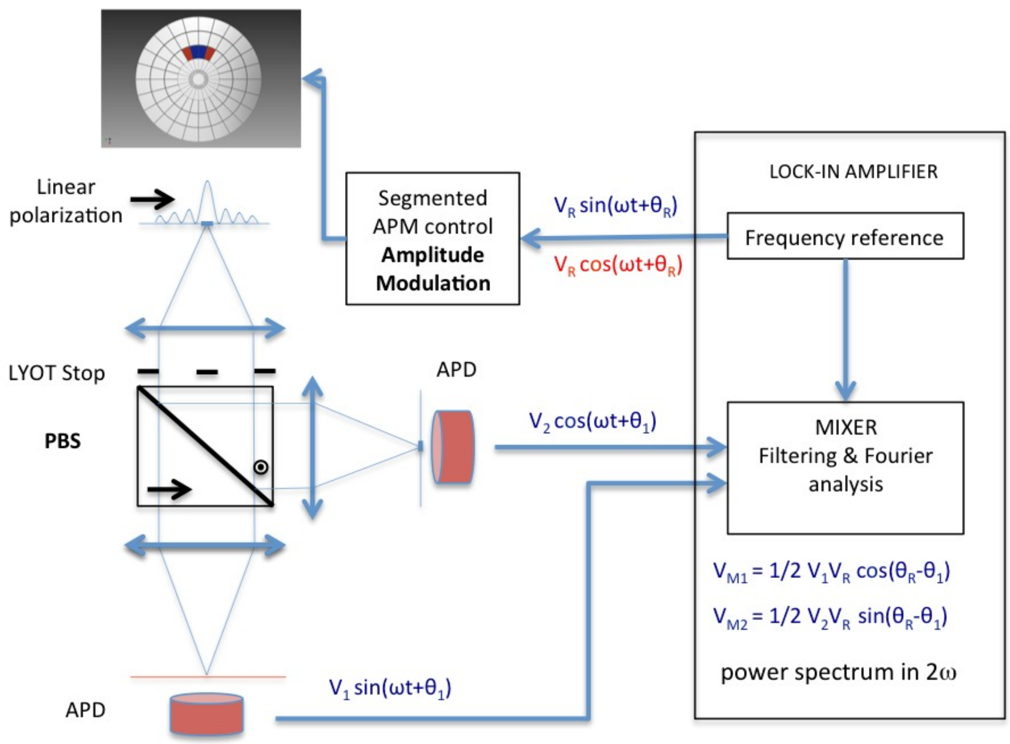

Figure 3. The synchronous demodulation process is equal in the AM and PM configurations. The spectrum analysis will detect the 2ω peak of modulation if a non uniformity of flux is present in the focal plane (speckle or companion).

2.3 Phase modulation

The mapping of static speckles or companion signatures is done in the focal plane around the central star by the amplitude modulation analysis as a first step. This mapping is verified by the viewer detector and provides the correspondence between the pixels of the detector and the pie charts of the APM (Figure 4).
To disentangle a companion signature from a static speckle, a pure phase modulation is done at the locations detected in the first AM step. Taking out the first polarized beam splitter, no modulation of transmission will be performed by the APM. The pie chart APM will only modulate the rotation of polarization inducing a phase delay from –π to π for each segment. The phase modulation of a speckle will induce an amplitude modulation detected by the APDs due to the coherence with the central star; in the case of a companion (incoherent) no modulation will be detected. The detection by

the photodiodes can be done simultaneously in two perpendicular linear polarization states by the APDs to increase the contrast of the interference, and therefore the sensitivity.

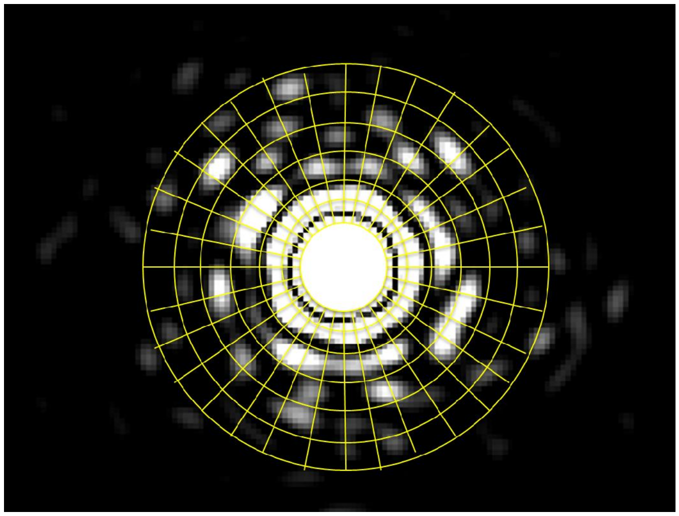

Figure 4. The figure shows the image of a star at the output of a Roddier coronagraph, and in the presence of residual speckles over which the segmented APM is placed. The speckles detected during the AM process are now modulated in phase one by one (or using multiplexing). The phase modulation is performed addressing a voltage modulation on the pie charts electrodes where the speckles were found.

Numerical simulations show that the modulation of intensity obtained by a pure phase modulation is a linear function of the speckle intensity in log scale. For instance, a phase modulation of a speckle with a relative intensity of 10^{-6} will induce a 0.05 % modulation of the global flux (see Figure 5). Note that the phase-induced intensity modulation will appear at half the frequency of the response produced by the amplitude modulation. Due to the geometrical phase, the peak in the Fourier space is at half the frequency of the one obtained in the first step.

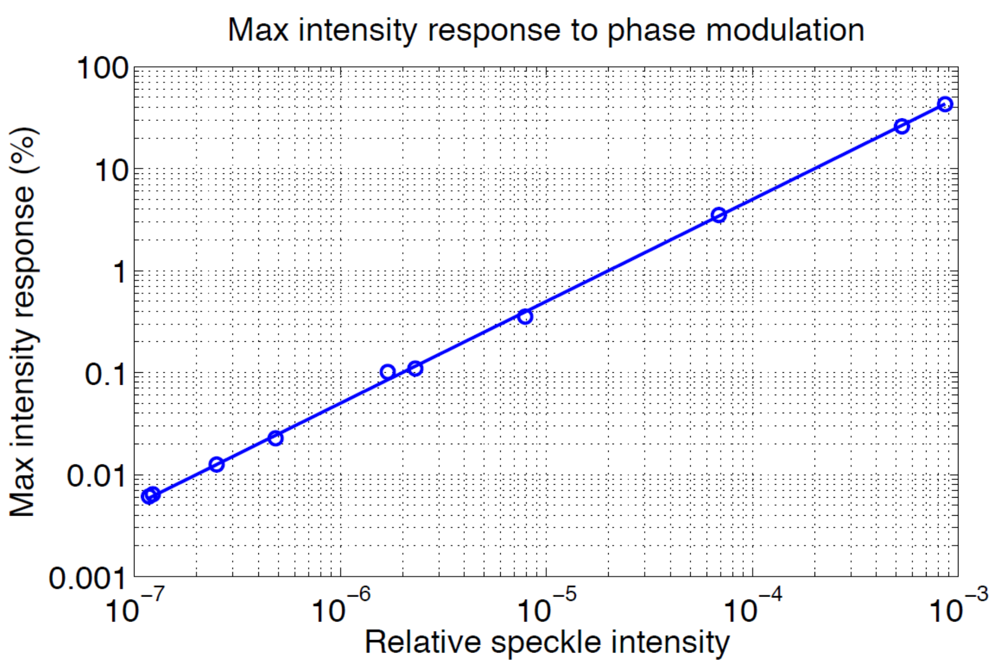

Figure 5. The vertical axis corresponds to the percent of modulation of the flux measured by the APD. A phase modulation of a speckle with a relative intensity of 2.10^{-5} induces a 1% intensity modulation integrated on the APD. The relative speckle intensity is at the output of the coronagraph stage.

In the case of an 8-meter telescope with an optical band pass of 500nm centered at λ=550 nm and a global throughput T=0.4, a V=0 mag speckle will contribute to the following zero-point flux on the APDs: $F^* = 10^{12}$ ph e-/s.

The sensitivity of the technique is limited by the quantity of photons that the system (APD or photomultiplier) will receive when working with a modulation at a carrier frequency. In principle the photon noise limited sensitivity is Qlim ~ 20 ph e- (theoretical case without thermal background). To be conservative and account for practical sources of noise, let us assume a Qlim = 200 ph e- as in the advanced detection systems for telecommunication (note that high quality APD and lock-in amplifiers could approach the photon noise limit). This detection limit translates to 2.5 log(F*/200/500) = 17.5 mag at 500 Hz, or 2.5 log(F*/200/50) = 20 mag at 50 Hz.

These sensitivity values represent “realistic” baselines for future instruments with “state of the art” electronics. However, let us note that the quality of the phase modulation might also degrade the efficiency in practice.

3. CONCLUSIONS AND PERSPECTIVES

The flexibility offered by the use of the geometrical/Pantcharatnam/Berry phase and dynamically driven liquid crystals enables a whole new kind of coronagraph design. In a first paper we presented the “Extinction-controlled Adaptive Phase Mask, APM” (Bourget et al. 2013) focused on the active control of the effects of both the phase-mask diameter with respect to wavelength, and the image instabilities (tip-tilt, Strehl ratio variability, etc.). This paper presents the instrument concept of the APM^2 coronagraph that holds the promise of high dynamic range detection capabilities. The capability to modulate, in Phase and in Amplitude, localized areas of the image is used to help distinguish between putative companions and speckles. The temporal modulation enabled by the use of liquid crystals associated with the extreme sensitivity of the synchronous detection techniques help retrieve faint signals from a noisy quasi-static background. This time- and cost-effective technique could greatly optimize the observation strategy with classical extreme-AO coronagraphs by vetting targets in advance (binaries), but would also enable large-scale surveys of stellar populations, looking for binarity statistics, which is a scientifically rich niche still largely unexploited.

Acknowledgements: This work was carried out at the European Southern Observatory (ESO) site of Vitacura (Santiago, Chile).

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