Cheapest nuller in the World: Crossed beamsplitter cubes

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Design

• General view of the crossed-cubes nuller

(Zemax™ artwork)
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Principle

- Two “crossed” beamsplitter cubes have their semi-reflective (SR) perpendicular one to the other
- The input beams propagates parallel to both cubes SR layers
- It is spitted into four parallel beams, being recombined axially
- A null is created at the focal plane centre
- It is independent of polarization orientation and of wavelength (at least theoretically)
- This is actually an Achromatic phase shifter
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Cubes polarization model

Cube 1

Cube 2

Sub-Pupil 1

Sub-Pupil 2

Sub-Pupil 3

Sub-Pupil 4

X' Polarization

Y' Polarization

X' Polarization

Y' Polarization

X' Polarization

Y' Polarization

X' Polarization

Y' Polarization

Beam 1

Beam 2

Beam 3

Beam 4
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Used as a coronagraph

- High throughput
- Output baseline $B'$ can be adjusted via cubes translation

$$B' = A \left(1 - \tan \theta\right) - 2h = A \left(1 - \frac{1}{\sqrt{2n^2(\lambda) - 1}}\right) - 2h$$

- Very small Inner working angle

$$IWA \approx \frac{1}{4} \frac{\lambda F'}{B'F} \approx \frac{1}{4} \frac{N' \lambda}{N D}$$

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- Primary Mirror
- Secondary Mirror
- Relay optics
- Focal plane
- Wavefront sensor
- Crossed-cubes nuller
- Multi-axial combiner
- Monolithic telescope
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Used as a nulling combiner

From collecting telescopes

Crossed-cubes nuller

Telescope 1

Relay optics 1

Metrology beams 1-4

Metrology beams 14-23

Metrology beams 2.3

Metrology beams 1-4

Metrology beams 2-3

Crossed-cubes nuller

Relay optics 2

Telescope 2

O

Z

O'

B

O''

F'

More photons
Narrower IWA
Used as a nulling combiner

- Fizeau interferometers → Input and output baselines $B$ and $B'$ are matched by sizing the cube hypotenuse $A$

$$B' = A \left(1 - \tan \theta\right) - B = A \left(1 - \sqrt{2n^2(\lambda) - 1}\right) - B$$

- Other configurations are possible (e.g. X-array)
- Maximal densification is also feasible → better for nulling interferometers, cf. paper 9146-89
Nulling maps at image plane

X’ Polarization

Y’ Polarization

Unpolarized
Preliminary manufacturing requirements

- If OPDs are compensated for by optical delay lines, there remains one tight specification: Flux balance < 0.1 %

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>REQUIRED VALUE</th>
<th>EQUIVALENT NULLING RATE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength</td>
<td>$\lambda = 10 \ \mu m$</td>
<td></td>
<td>Depending on science requirements</td>
</tr>
<tr>
<td>Spectral range</td>
<td>8-12 \ \mu m</td>
<td></td>
<td>Depending on science requirements</td>
</tr>
<tr>
<td>Semi-reflective layer (SR)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission factor</td>
<td>$50 \pm 0.1 %$</td>
<td></td>
<td>On full spectral band</td>
</tr>
<tr>
<td>Reflection factor</td>
<td>$50 \pm 0.1 %$</td>
<td></td>
<td>On full spectral band</td>
</tr>
<tr>
<td>Flux mismatch</td>
<td>&lt; 0.1 %</td>
<td>$1.0E-06$</td>
<td>On full spectral band</td>
</tr>
<tr>
<td>Anti-reflective coating (AR)</td>
<td>Standard</td>
<td></td>
<td>$\lambda/4$ AR coating</td>
</tr>
<tr>
<td>Geometrical parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cube hypotenuse</td>
<td>$75.5 \pm 0.1 \ mm$</td>
<td></td>
<td>Case of ZnSe material</td>
</tr>
<tr>
<td>Transmitted pathlength in glass</td>
<td>$21.4 \pm 0.1 \ mm$</td>
<td></td>
<td>Case of ZnSe material</td>
</tr>
<tr>
<td>Reflected pathlength in glass</td>
<td>$21.4 \pm 0.1 \ mm$</td>
<td></td>
<td>Case of ZnSe material</td>
</tr>
<tr>
<td>Pathlength difference in glass</td>
<td>&lt; 0.005 $\mu m$</td>
<td>$9.8E-06$</td>
<td>Only applicable to coronagraph</td>
</tr>
<tr>
<td>Angular errors</td>
<td>&lt; 3 arcmin</td>
<td>$7.6E-07$</td>
<td>For both SR/AR faces, including pyramid</td>
</tr>
<tr>
<td>Wavefront error</td>
<td>&lt; $\lambda/4$ PTV</td>
<td>$0.0E+00$</td>
<td>For both transmitted and reflected beams, on</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>each sub-pupil</td>
</tr>
<tr>
<td>Total Null (RMS sum)</td>
<td></td>
<td>$4.6E-06$</td>
<td></td>
</tr>
</tbody>
</table>
Main advantages

- Simple, compact, low mass and volume
- Reasonable manufacturing tolerances
- Potentially not expensive
- High throughput, close to maximum
- Can be implemented into a nulling coronagraph telescope or a sparse-aperture nulling interferometer
- Very small Inner working angle (IWA) when used as a coronagraph
- Capacity for fringes rotation and baseline modulation
- Good candidate for future space missions characterizing extra-solar planets atmospheres
Conclusion

- **“Cheapest nuller in the World”**? Yes, for producing “quick and dirty nulls” (e.g. student courses)
- Probably a little bit more expensive if very deep nulls are required
- Alternative title: “**PERSEE interferometer in a nutshell**”