Generation of intense few-cycle pulses from the visible to the mid-IR

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Goals

**Axicon**
- Generate an aligned Bessel Beam with an Axicon
- Propagate a Bessel Beam through a Hollow Core Fiber (HCF) and measure the power
- Quantitatively characterize our experimental Bessel Beams

**Generation of mid-IR fs pulses**
- Create a setup to prove the generation of mid-IR pulses (5 - 10 μm) with femtosecond pulses
- Measure efficiency as a function of angle of the Difference Frequency Generation (DFG) type II crystal in mid-IR region

**Motivation for Both Projects**
To study strong field physics in the mid-IR range
Axicon Terminology

• Axicon: conical lens that can be used to create a Bessel Beam
• Bessel Beam: a circular beam with ring like structure
• Hollow Core Fiber: a glass rod with a small hollow core that is used to guide light
Axicon Terminology

• Few cycle pulse: A pulse of light that has few optical cycles

Diagram from Dissertation by Nora Kling (2013)
Axicon Setup

- HeNe Laser
- Neutral Density filter
- 4x magnification telescope
- 500 mm lens
- 178 Degree axicon
- 93 mm
- 355 mm
- 1 meter long, 250 μm diameter hollow core fiber
Determining Axicon and Fiber Distance

- Needed a beam smaller than 250 μm entering fiber

![Graph showing diameter of smallest beam vs distance of axicon from lens with linear fit.](image1.png)

![Bar graph showing distance to smallest beam for varying distances of lens to axicon.](image2.png)

Bessel Image from rsc.org
Theoretical Analysis

1. Created a program in Matlab to make a nice 2-d quantified representation of a Bessel Beam

\[ S(r, \theta) = \left( \sum_{m=0}^{M} \sum_{n=0}^{N} c_{nm} J_n(\alpha_n^m r/p) e^{i n \theta} \right)^2 \]

\[ c_{nm} = \int_0^a \int_0^{2\pi} J_n(\alpha_n^m r/p) e^{i n \theta} \sqrt{S(r, \theta)} r \, dr \, d\theta \]

\( S(r, \theta) = \) experimental distribution
\( J_n = n^{th} \) order Bessel Function
\( \alpha_n^m = m^{th} \) Bessel zero of \( J_n \)
\( p = \) scaling constant for Bessel zeros
\( c_{nm} = \) coefficients retrieved from program
Data Analysis

2. Created a program in Matlab to programmatically analyze the data and give a nice color scheme
Data Analysis

3. Created a Matlab program to make a video of the propagation of a Bessel Mode after an axicon.

Pictures taken at 2.5 mm steps along propagation from 155 mm to 200 mm
Axicon Results

Power before fiber = 3.72 mW with axicon and 4.03 mW without axicon

<table>
<thead>
<tr>
<th>Inner Diameter (μm)</th>
<th>Transmitted Power (mW)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>2.08</td>
<td>55.9</td>
</tr>
<tr>
<td>300</td>
<td>0.36</td>
<td>9.7</td>
</tr>
<tr>
<td>350</td>
<td>0.78</td>
<td>21.0</td>
</tr>
<tr>
<td>400</td>
<td>0.77</td>
<td>20.7</td>
</tr>
<tr>
<td>450</td>
<td>0.48</td>
<td>12.9</td>
</tr>
<tr>
<td>500</td>
<td>0.40</td>
<td>10.8</td>
</tr>
<tr>
<td>500 mm lens</td>
<td>2.32</td>
<td>57.6</td>
</tr>
</tbody>
</table>

300 – 500 μm fibers are new and a different brand. It is not conclusive whether they are bad fibers or not.
Mid-IR fs Pulse Generation Terminology

- Optical Parametric Amplifier (OPA): Non-linear device that takes pulsed laser light and for our case produces two beams; a signal (1050 – 1550 nm) and an idler (1600 – 2500 nm); Signal and Idler are about 40 – 50 fs

- Difference Frequency Generation (DFG): takes two beams (signal and idler) and for our case creates one beam (3-12 μm)

\[
\frac{1}{\lambda_{\text{DFG}}} = \frac{1}{\lambda_s} - \frac{1}{\lambda_i}
\]

\[
\omega_{\text{DFG}} = \omega_s - \omega_i
\]
Mid-IR fs Pulse Generation Setup

Almost 0 transmission from 0 – 1.8 μm

Mid-IR Transmission that we want

Transmission graph from thorlabs.com
Mid-IR fs Pulse Generation Results

• Showed generation of mid-IR fs pulses through crystal with Phase Matching

<table>
<thead>
<tr>
<th>Beam</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>1490</td>
</tr>
<tr>
<td>Idler</td>
<td>1750</td>
</tr>
<tr>
<td>Mid-IR fs pulse</td>
<td>9200</td>
</tr>
</tbody>
</table>

\[ \frac{1}{\lambda_{DFG}} = \frac{1}{\lambda_s} - \frac{1}{\lambda_i} \]

• Signal and Idler achieve optimum phase matching at 0 (or 360) and 130 degrees
Mid-IR fs Pulse Generation Results

- With tuning and crystal rotation of 134 degrees:

\[ \frac{1}{\lambda_{DFG}} = \frac{1}{\lambda_s} - \frac{1}{\lambda_i} \]

<table>
<thead>
<tr>
<th>Observed Phenomena</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power of generated Mid-IR fs pulse</td>
<td>10.5 mW</td>
</tr>
<tr>
<td>Wavelength of signal at max power</td>
<td>1450 nm</td>
</tr>
<tr>
<td>Wavelength of idler at max power</td>
<td>1705 nm</td>
</tr>
<tr>
<td>Energy Split</td>
<td>66% signal 34% idler</td>
</tr>
<tr>
<td>Wavelength of generated Mid-IR fs pulse at max power</td>
<td>9700 nm sub 100 fs pulse</td>
</tr>
</tbody>
</table>
Mid-IR fs Pulse Generation Results

Almost 0 transmission from 0 – 1.8 μm

Transmission that we want

$1/\lambda_{\text{DFG}} = 1/\lambda_s - 1/\lambda_i$

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<td>Mid-IR fs pulse</td>
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Power of Mid-IR fs pulses for varying setups

Original: 12 mW
No DFG crystal: 2 mW
Axicon
The Bessel Beam from the axicon coupled through a 250 μm fiber almost as well as just the lens.

Mid-IR fs pulse generation
We were able to create 10.5 mW light at close to 9.7 μm (mid-IR) sub 100 fs pulses which is an awesome result.
Future

Axicon
• We expect to improve the transmission efficiency by changing the focusing conditions and the fiber diameter.
• As soon as the Bessel Beam travels through the fiber more efficiently, we can use this method to have more efficient spectral broadening for fs pulses.

Mid-IR fs pulse generation
• We are going to adjust our Mid-IR fs pulse generation setup to better control the phase matching of the signal and idler in order to create higher power Mid-IR fs pulse beams.
• We are going to attempt the Mid-IR fs pulse setup in HITS
Acknowledgements

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