Development of a Dammann Grating to Study Kramers-Kronig Self-Phasing in Coherently Combined Fiber Lasers

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Introduction:

The goal of this project was to develop a Dammann grating to couple a three core fiber laser as illustrated in figure 1. By coupling the fiber lasers a resonance cavity was formed similar to the optical system in reference 3. A Dammann grating is a diffractive optic that splits the wave front of incident light into multiple orders [1,2]. With prior knowledge of the input, the Dammann grating's power distribution and spacing was specified before fabricating the structure.

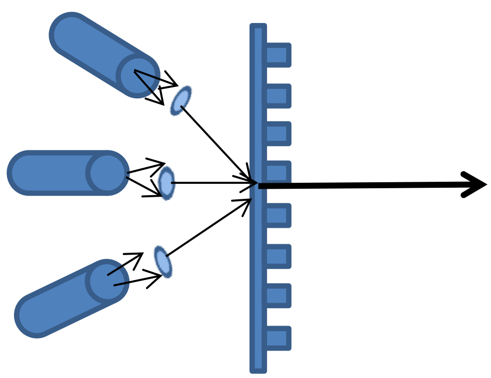


Figure 1, Combining of coherent beams using a Dammann grating.

In this experiment, the Dammann grating also served as a way to apply a well-known phase difference between the fiber cores. With this fiber system, self-phasing effects attributed to the Kramers-Kronig effect were studied by applying a phase difference to the fibers by translating a Dammann grating inside of the cavity. In order to limit other phase shifting effects the fibers were designed in close proximity in order to limit nonlinear effects due to temperature fluctuations. The fiber system was also pumped just above the lasing threshold in order to limit nonlinear effects from the optical Kerr effect [3].

The importance behind this study was to obtain a deeper understanding behind the Kramers-Kronig effect to improve coherent laser beam combining. By understanding these self-phasing effects new fiber systems can be developed with diminished loss. As a result, it is possible to implement more efficient fiber lasers for use in non-invasive biological studies, industrial applications, and optical communications.

Theory:

When a beam of light with wavelength λ is incident on a diffractive surface with a periodic structure the orders of light that are emitted have a spacing that is related to the period, Λ, of the grating as shown in equation 1. However, the power in each of these orders is not determined by equation 1 [1].

$$\sin\theta = m\,\lambda/\Lambda \qquad \text{Equation 1}$$

In order to understand the power distribution of the orders the amplitude transmittance function of the Dammann grating must be specified. In equation 2 below, the transmittance of the Dammann grating is defined as a binary grating in both the x and y direction. In order to define the whole structure of the grating the transmittance function is then convolved with a comb function. Since the incident beam is much smaller than the Dammann grating this is all the further treatment needed.

$$t(x,y) = \mathrm{rect}(x/b_x)\mathrm{rect}(y/b_y)\otimes\delta(x+b_x/2, y+b_y/2)$$
$$+\mathrm{rect}[x/(\Lambda_x-b_x)]\ \mathrm{rect}[x/(\Lambda_x-b_y)]\ \otimes \delta[x-(\Lambda_x-b_x)/2, y-(\Lambda_y-b_y)/2]e^{i\varphi} \qquad \text{Equation 2}$$

The light incident to the Dammann grating is assumed to be planar. Therefor the amplitude and phase of the diffracted orders is described by the Fourier Transform of the transmittance function, convolved with a comb function, as shown in equation 3. By taking the squared modulus of equation 3 the intensity of each order is realized in equation 4. Finally the individual power or total power of the diffracted orders was calculated by integrating intensity over the surface profile [1,4].

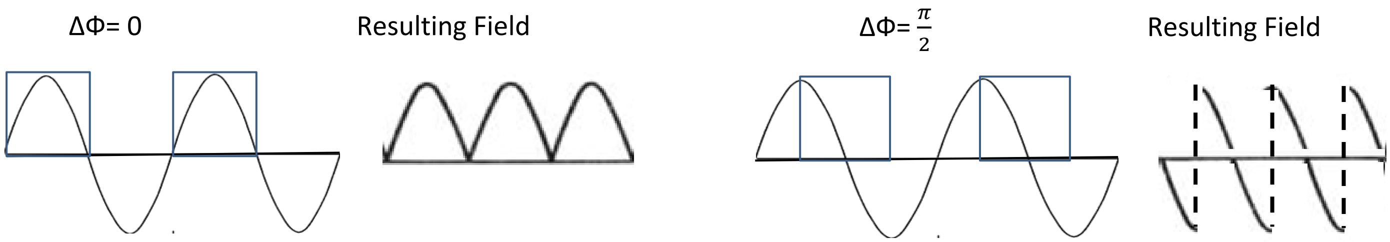
$$F(q,w) = \frac{b_x b_y}{\Lambda_x \Lambda_y}\mathrm{sinc}(b_x \mathrm{q})\ \mathrm{sinc}(b_y \mathrm{w})\mathrm{exp}(\mathrm{j}2\pi(q b_x + w b_y)/2) + \frac{(\Lambda_x - b_x)(\Lambda_y - b_y)}{\Lambda_x \Lambda_y}\ \mathrm{sinc}((\Lambda_x - b_x)\mathrm{q})\ \mathrm{sinc}((\Lambda_y - b_y)\mathrm{w})\mathrm{exp}(\mathrm{j}2\pi\ (q(\Lambda_x - b_x) + w(\Lambda_y - b_y))/2) \qquad \text{Equation 3}$$

$$|F(q,w)|^2\left(q = \frac{m}{\Lambda_x}, w = \frac{n}{\Lambda_x}\right) = A^2\ \mathrm{sinc}^2(\mathrm{m}/2)\ \mathrm{sinc}^2(\mathrm{n}/2)\mathrm{sin}^2(\mathrm{m}\pi/2)\ \mathrm{sin}^2(\mathrm{n}\pi/2) \qquad \text{Equation 4}$$

The final structure of the Dammann grating that should be noted is the features depth. The depth, d, of the features is directly proportional to the wavelength of light entering the grating, the phase of the grating, and inversely proportional to the index of refraction of air and glass as shown in equation 5. The depth is chosen this way so that it is equal to a half-wavelength path length difference [1].

$$\mathrm{d} = \frac{\Phi\, \lambda}{2\pi(n_{glass} - n_{air})} \qquad \text{Equation 5}$$

In this experiment, a Dammann grating cavity was formed with the grating described above. When the interference pattern from the mutually coherent fiber lasers is incident on the grating the highest power output is achieved by making sure the period of the sinusoidal interference pattern and the grating match up. As the phase difference between the grating and the interference pattern increases the power output should decrease as shown in figure 2 below. However, due to the self-phasing effects of the Kramers-Kronig effect the phase difference between the interference pattern and the Dammann grating should cause minimal change to the power output of the fiber system [5].



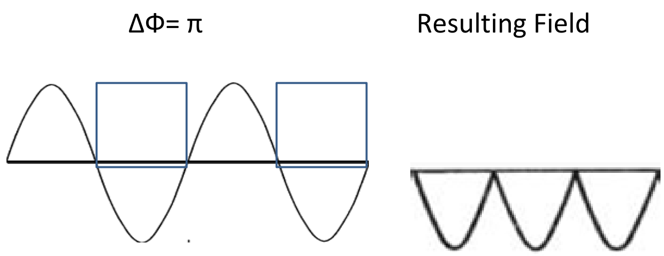


Figure 2, Illustration of the period of the interference pattern matching up with the period of the grating. From left to right slowly shows the interference pattern going out of phase and the resulting field.

Apparatus/Methods:

Featured below is a 2D and 3D diagram of the Dammann grating used for this project along with all of the gratings dimensions. This grating was fabricated using optical photolithography and wet etching techniques. For exact methods used to fabricate this grating refer to reference 6.

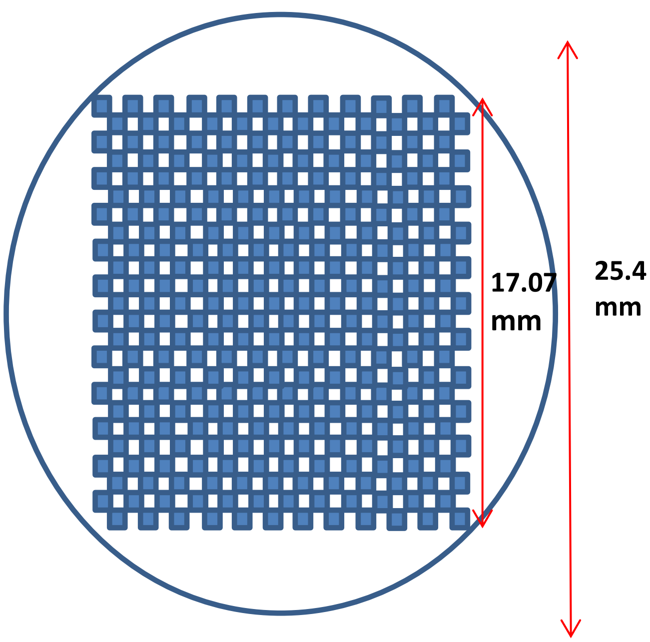


Figure 3, A diagram of the dimensions of the glass substrate and the pattern etched on to the substrate.

Dimensions:

$b_x = b_y = 711.25\mu m$

$\Lambda_x = \Lambda_y = 1422.5\ \mu m$

d= 1.1737 μm

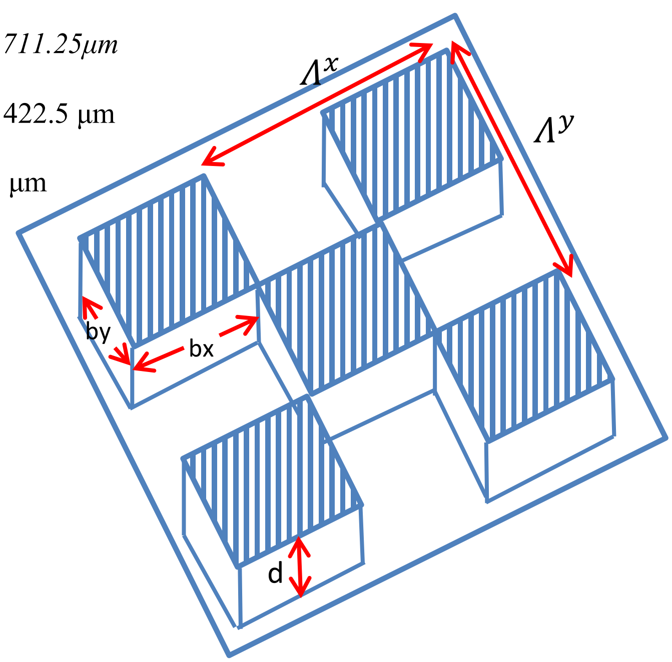


Figure 4, A 3D close up of the fabricated Dammann grating.

After fabrication, the Dammann grating was then used to couple the fiber lasers and form a resonance cavity. Figure 5 shows the half of the resonance cavity that contains the Dammann grating. It was with this portion of the system that the power output was measured, with a power meter, as a function of applied phase. In comparison to past experiments, this experiment was capable of applying a phase in both the x and y direction by translating the Dammann grating in the x and y directions both individually and simultaneously [3,7].

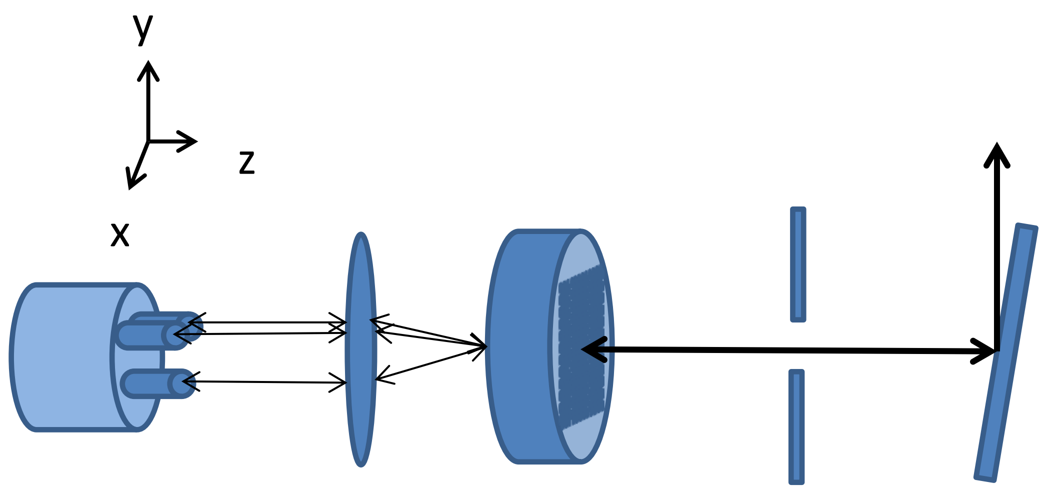


Figure 5, a diagram of the fiber system showing the individual light from the fiber cores being collimated, coupled, and then reflected out of the cavity.

Results:

Below are the results from measuring the power output as a function of applied phase. In figure 6, the power output varies as would be expected for a Dammann grating cavity. However, this measurement was made below the lasing threshold of the laser used to pump the system. In figure 7, the laser is turned just above threshold and it is evident that even at a large applied phase there are smaller fluctuations in power. These phase correcting properties are attributed to the KK effect because many of the other self-phasing mechanisms have been eliminated through careful design and fabrication.

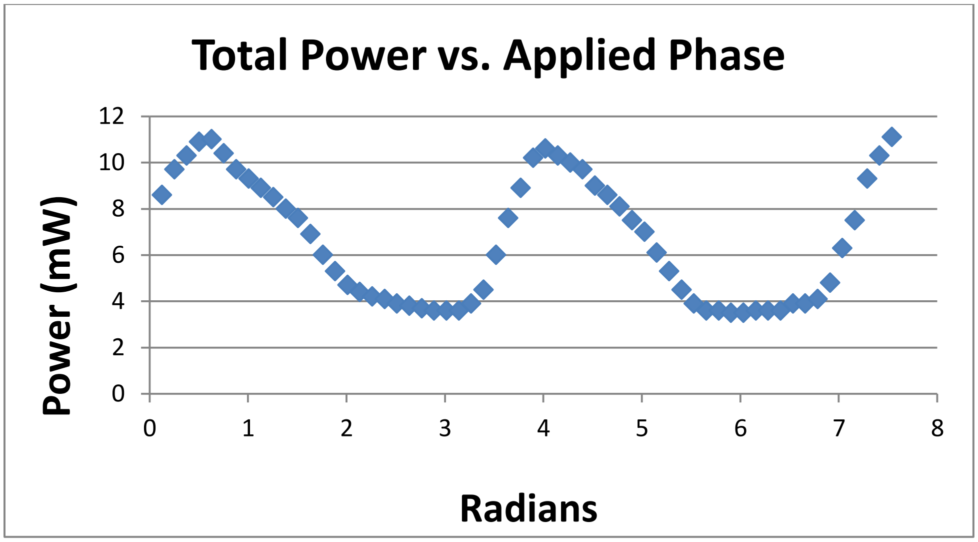


Figure 6, power measurement of the fiber system just under lasing threshold. No self-phasing is evident.

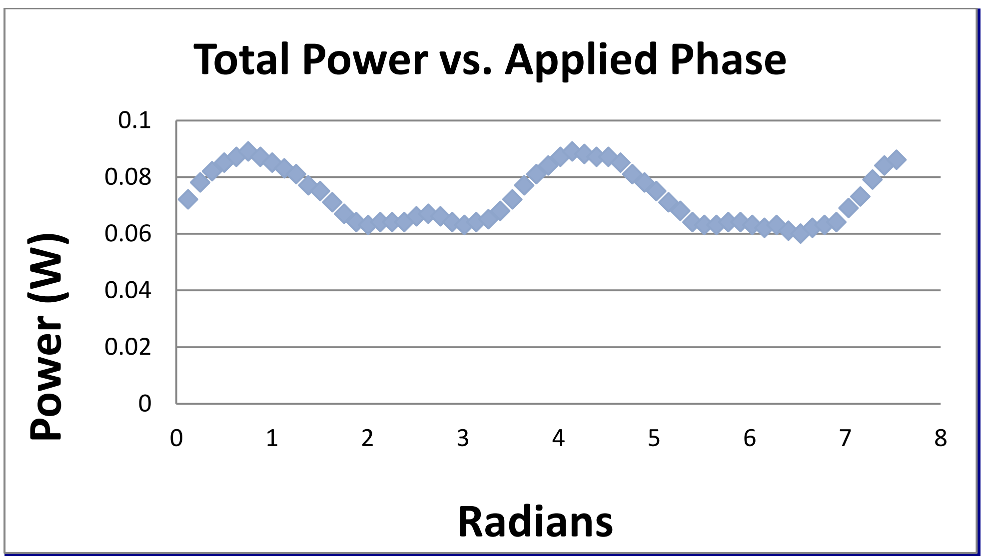


Figure 7, power measurement of the fiber system just above lasing threshold. It can be seen here that even with a large phase difference the amount of power loss during that period has lessened.

Self-phasing attributed to the KK effect has already been shown by applying phase in one dimension by reference 3. However, with the Dammann grating fabricated for this experiment, it was possible to apply phase in the x and y simultaneously. In figure 8, the result from applying phase in two dimensions is shown. Once again self-phasing is evident in figure 8 because there is little fluctuation in the output power of the fiber laser no matter what the phase difference.

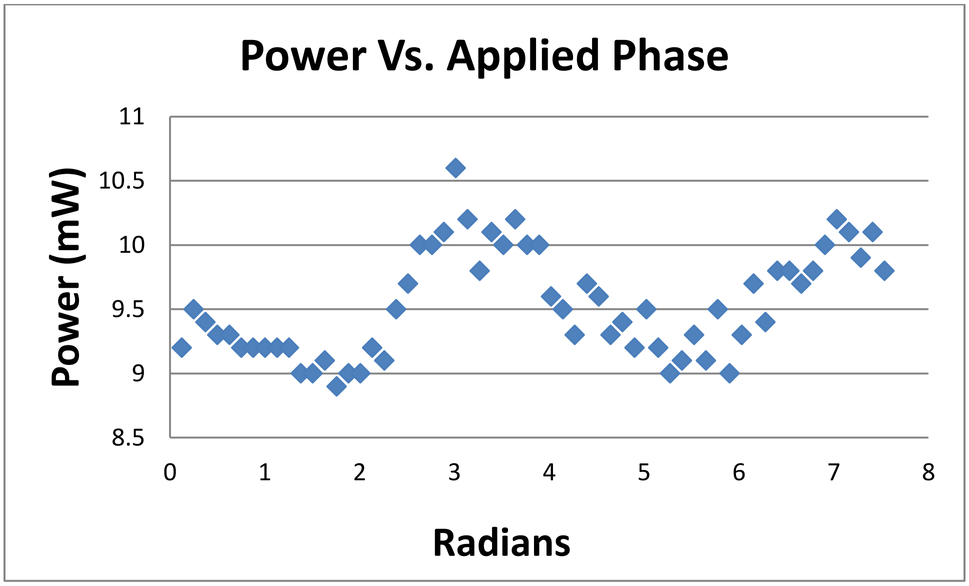


Figure 8 , power measurement of the fiber system with applied phase both in the x and y direction. This figure shows that self-phasing effects due to the KK effect in a three fiber core system can occur.

Conclusion:

This projects main focus was in designing and fabricating a Dammann grating to couple fiber lasers and study self-phasing mechanisms. By forming a Dammann grating cavity and applying a phase difference between the fibers cores a deeper understanding of the Kramers-Kronig effect was achieved. Not only has self-phasing of two fibers been shown again due to the KK effect, but it has now also been shown to occur in a three fiber system.

Bibliography:

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