# *Frequently Asked Questions - Liquid Crystal Polarization Gratings*

Most of the commercial interest in Liquid Crystal Polarization Gratings has been for non-mechanical beam steering and so that is the current focus of this document. Please inquire directly regarding LCPG tunable lens assemblies and individual LCPG and LCP lens components.

## What wavelengths work best with LCPGs?

Meadowlark can efficiently fabricate LCPGs with design wavelengths from 450 nm to ~1700 nm, and other wavelengths are possible.

It becomes more difficult below 450 nm to get good quality LCPGs with high optical efficiency. A challenge is getting the LCP layer thin enough to achieve the necessary λ/2 retardance at the design wavelength.

Wavelengths from ~1700 nm to ~2500 nm are possible. They require advanced spectrometry to dial in the LCP layer thickness when spin coating.

MWIR and LWIR parts can be made by photo-aligning two substrates and then gapping them and filling them like a conventional LC cell (with no ITO.) The LC adopts the grating orientation in the cell. This sophisticated technique results in a thicker (two glass substrates) product with slightly less optical efficiency but can achieve the desired wavelengths.

MWIR and LWIR beam steering also creates challenges for the LC cells and index matching of the components to one another, due to absorption in transparent conductors and index matching adhesives.

All MWIR – LWIR and < 450 nm requests are developmental efforts that are evaluated by engineering.

## What is the maximum total steering angle?

Meadowlark can make individual gratings with grating pitches down to ~7.5 µm. This is not a hard cut-off, but getting the patterning station down to < 7 µm can be physically impossible for most beam sizes of interest.

The diffraction angle for a grating follows:

$$\sin(\theta) = \lambda/d, \qquad (1)$$

which equates to roughly the following maximum single grating angle at the following wavelengths:

**532 nm: ±4°**
**1064 nm: ±8°**
**1550 nm: ±12°**

This tells you how many gratings (at minimum) would be required for a beam steering assembly of a given field of view.

For full beam steering assemblies consisting of multiple stages, where a stage is one or more gratings paired with an LC cell, the **largest total steering angle we have built is ±54° × ±9°,** covering 120° × 25° full field after input from a MEMS scanning mirror.

## What angular step size can be used?

The required angular step size combined with the total field of regard determines the number of stages required:

$$N_{ANGLES} = \theta_{FOV} / \Delta\theta + 1 \qquad (2)$$

where θFOV is the total field of regard, Δθ is the angular resolution, and NANGLES is the number of steering angles.

The number of steering angles (NANGLES) tells you how many stages (NSTAGES) will be needed in that axis, where the maximum number of angles that can be:

$$N_{ANGLES}=2^{\wedge(N\_STAGES)}. \qquad (3)$$

So, let's say a customer wants a total field of regard of 26° with 2° angular step size. By Eq. 2, that will require 26/2+1 = 14 steering angles. A 3-stage system can only get us up to 23 = 8 steering angles, so we would need a 4-stage design.

Note that the largest number of stages we have ever built is 14, and that is a very difficult build.

To achieve a fine angular step size that would require many stages with an LCPG alone, pair an LCPG with a fine-angle steering technology (e.g., MEMS, fast steering mirror, SLM, etc.) for optimal results.

## Can steering be a one-axis or two-axis design?

The preceding discussion covers one axis of steering. 2D steering is not a problem; we add gratings that are rotated by 90 degrees to provide steering in the other axis.

So, in our previous example of 26° field of regard with 2° steps, if you need that in both axes, the resulting design will have 8 total stages instead of 4.

**Note:** the total steering field of regard and the angular resolution need not be the same for each axis.

## What size is the clear aperture?

The clear aperture is limited by three factors:

### 1. The size of substrates that we can process

We can process up to 22 cm substrates currently in our grating process. However, anything beyond 10 cm requires expanding the beam up more than we normally do and requires longer exposures that are more sensitive to vibration and other environmental changes. We consult engineering before quoting anything larger than 10 cm aperture.

### 2. The walk-off of the beam as it gets steered by each stage

This is ultimately best calculated through our in-house Matlab-based simulation capability. But it can be easily visualized that a beam steering at 10° and traversing 15 mm of glass, for example, will walk-off by the time it emerges from the exit aperture.

For an overly conservative estimate, you can simply take the tangent:

$$\tan(\theta)*\text{thickness} = \text{walk-off}, \tag{4}$$

where θ here is the steering angle in a single direction. So, in the previous example, a beam steering assembly with a total steering field of regard of ±10° and 15 mm total thickness would have tan(10°)×15 mm = 2.6 mm of walk-off at the exit aperture.

Because it is single-sided, the clear aperture would need to increase by 2× that much to accommodate the full field. So, if you say they require a 10 mm input clear aperture, that need will increase to 10+2.6×2 = 15.3 mm at the exit aperture.

In reality, the smallest angle gratings are built closest to the input aperture so that the angle builds more gradually through the stack and so Eq. 4 is overly conservative, but it gives an idea of the magnitude.

### 3. Encroaching features such as the bonding ledges and gasket

We must allow for bonding ledges to attach the wires to the ITO on the LC cells and allow room for gasket in the LC cells. We have typically used 2 mm bonding ledges and 2 mm gasket width.

An LC cell typically has two bonding ledges with one on each of two opposing sides. This means that one axis of the substrate loses 4 mm of potential clear aperture to bonding ledges.

The LC cell gasket goes around the perimeter of the LC cell, meaning that both axes of the substrate lose 4 mm total of clear aperture to gasket.

So, in the example given before, a customer who needs 10 mm input clear aperture on a ±10° steering system with 15 mm thickness will require a substrate that is a bare minimum of 15.3mm + 8 mm = 23.3 mm in one axis and 15.3 mm + 4 mm = 19.3 mm in the other axis.

## What switching speed can LCPGs achieve?

Switching speed scales with design wavelength. We traditionally use LCM-2219 for the beam steering systems.

If a customer does not have strict speed requirements, a full wave cell at room temperature will usually yield optimum efficiency. Here the cell will be driven between its λ and λ/2 states.

If a bit more speed is needed, we would likely specify a half-wave cell. In this case the cell would be driven between its λ/2 and ~0λ states. We don't traditionally incorporate compensating retarders here, so the high voltage ~0λ state can be ~1% less efficient.

Note that when we speak about efficiency here, we are referring to the optical efficiency of an LCPG steering stage, where retardance error from the cell directly correlates to some small amount of light being steered to the wrong direction from the grating.

If you need even more speed, we can incorporate heaters into the design and operate at an elevated temperature. For the 2219 LC, typically this is 60°C, above which there can be diminishing returns for speed and increased LC disorder.

To give an idea for speed, here's **an example of the range of speeds we've quoted for 905 nm light in different scenarios**:

**Full-wave cell @ 25°C: < 8 ms**
**Half-wave cell @ 25°C: < 2 ms**
**Half-wave cell @ 60°C: < 1 ms**

LCPGs switch slower in the relaxation direction but faster in the rising direction. In the example given above, the 905 nm half-wave cell at 60°C relaxed (90%-10%) in 750 µs, but rising time was on the order of 25 µs.

In random access steering with the LCPG non-mechanical steering configuration, many cells are all transitioning at once when the pointing angle is changed, so we are usually limited by the cell relaxation time. However, it is possible to design scanning patterns that optimize rising transitions and then relax as many cells simultaneously as possible to minimize the relaxation transitions. With these special scanning patterns, roughly 2/3rds of the angles can be sampled with fast rising transitions. So, if there are 32 total angles to sample, the full field scan rate does not need to be 32× the relaxation time but can be faster if these fixed scanning patterns can be allowed.

## What efficiency will the LCPG have?

The optical efficiency of the LCPGs depends on many factors, but ultimately, it's going to boil down to two things: the number of steering stages and the total steering angle.

Each steering stage consists of one LC cell and at least one LCPG. Each of those components introduce losses. These losses are somewhat dependent on wavelength due to ITO absorption, but we can roughly estimate the efficiency per stage as ~96% when everything is properly index-matched together with AR end caps.

As steering angles get large, the diffraction efficiency of the gratings falls. Once the total steering angle of the system exceeds ~±10°, expect that this diffraction efficiency roll-off will begin to dominate.

For example, the ±54° × ±9° system mentioned earlier had 7 stages and ~30% efficiency out at the most extreme steered angles.

## What is the transmitted wavefront quality?

For NIR and SWIR systems that need < $\lambda/4$ RMS wavefront error, we use thin display glass, including the AR end caps.

For VIS systems where wavefront is a concern, or NIR-SWIR systems with wavefront of $\lambda/8$ RMS or better, we quote good, flat, optical-quality end caps. For larger aperture sizes, these can get to be somewhat thick and add to cost.

## Is there a difference between a laboratory system and one operated in the field?

Not much. Meadowlark has some environmental testing data and is still getting more. Generally speaking, the technology is robust to most environmental factors. If you will be doing field testing, integrated heaters may be required to stabilize the temperature, and you should avoid UV exposure.

## Can the system support bi-directional steering?

Yes! Some applications, such as lidar and free space optical communications, require bi-directional operation. Care must be taken in the design process to ensure the beam steering assembly will behave as desired.

Specifically, if you are transmitting light that will be backscattered to the LCPGs, and you wish to steer the returning light back through the same LCPG assembly, you will need additional polarization control at the "scene side" aperture. This is because the LCPG naturally transmits in circularly polarized states. To properly receive the backscattered light, it needs to be in the same polarization state as it went out: e.g., transmitted light in right-hand circular polarization will only retrace back through the LCPGs if it returns in right-hand circular polarization.

Circularly polarized light flips handedness on back-reflection. So, if you steer light out of an LCPG system without any further polarization control, it will return on the opposite handedness and will not make it back through the assembly to the "system side" aperture.

In the lidar example, we must use a λ/4 retarder so that the transmitted light is linearly polarized. Linearly polarized light does not change during back-reflection and so the light will retrace its path properly.

In free space optical communications, be aware that you will not be able to transmit on one handedness while receiving on the opposite handedness, as is sometimes done.