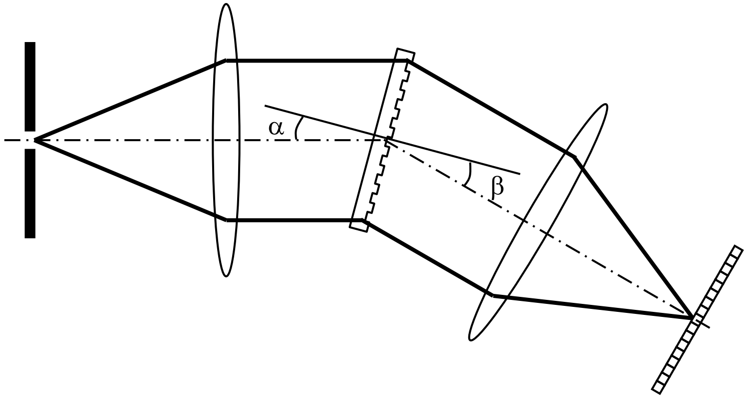
Spectrometer

Design Guide



Introduction

This guide provides some simple and easy to use design guidelines and formulas for designing, evaluating and comparing various diode array, diffraction grating based spectrometers designs

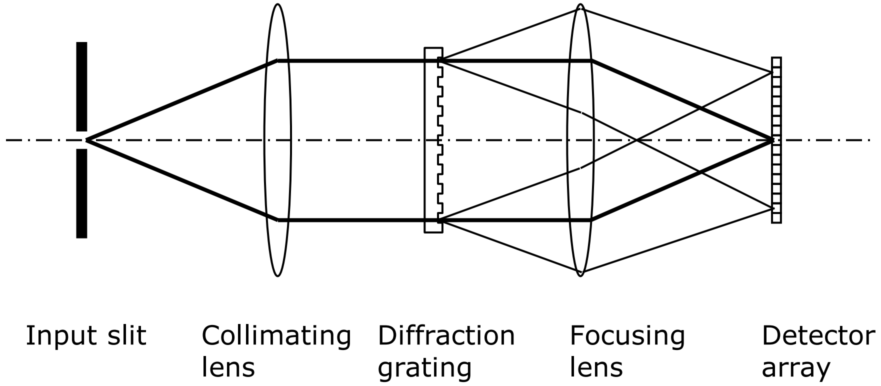
The input to the design process is the **wavelength range** you want to cover and the **optical resolution** by which you need to resolve the various structures in your spectrum (often peaks).

CAUTION !

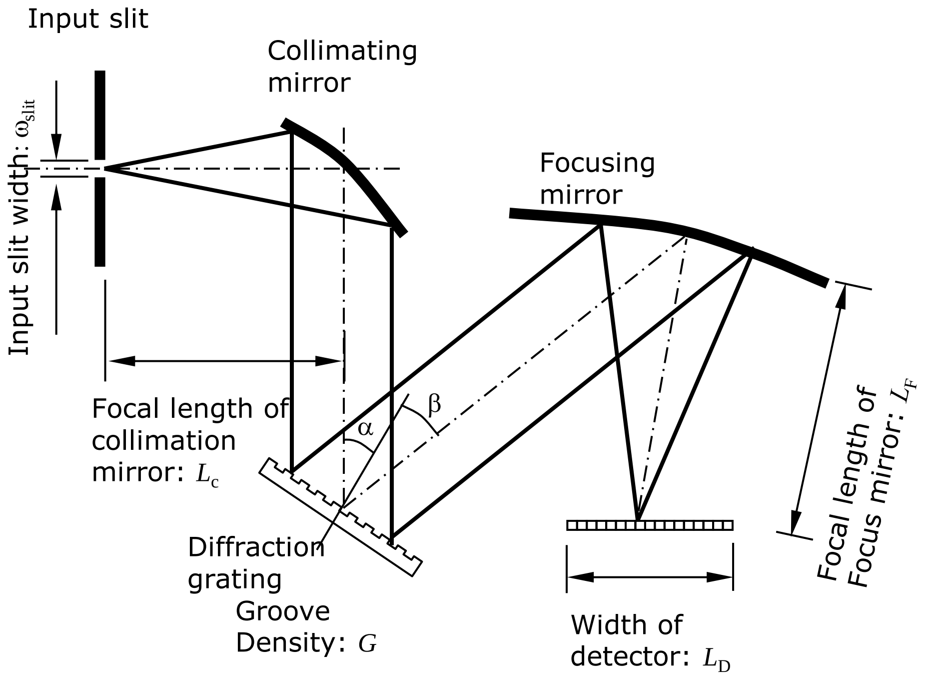
Spectometer designs made by using this guide **should only be used as a starting point** in your design process. If you are going to implement a spectrometer in hardware you should always use a numerical simulation tool (for instance geometrical ray tracing) to make the final design.

How a diode array spectrometer works

Basically, a spectrometer is an optical system consisting of two lenses/mirrors that produces an image of the input slit on the detector. In between the lenses/mirrors is placed a diffraction grating which disperses different wavelengths in different angles. This causes different wavelengths of light entering the input slit to be imaged to different position on the detector array.



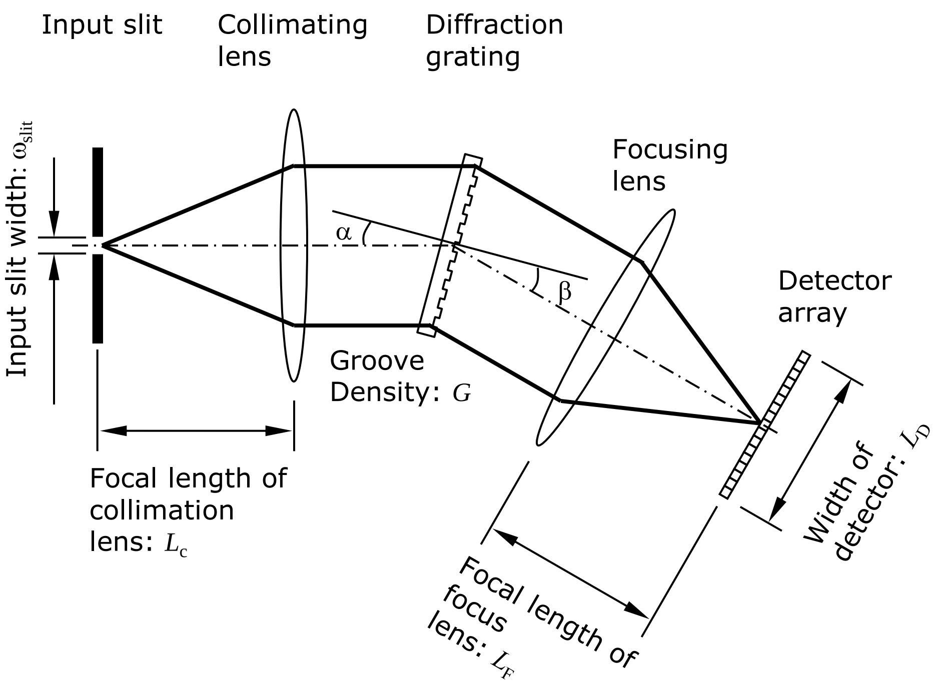
On the following pages are shown two common spectrometer geometries; the transmission grating based and the crossed Czerny-Turner. Also, the figures defines the key design parameters of a spectrometer.



Minimum wavelength: λ_1
Maximum wavelength: λ_2
Wavelength range: $\lambda_2 - \lambda_1$
Resolution: $\Delta\lambda$
Center wavelength: $\lambda_c = (\lambda_2 + \lambda_1)/2$

Angle of incidence: α
Diffraction angle: β
$\Phi = \alpha + \beta$

Grating groove density: G
Focal length collimation: L_C
Focal length focus: L_F
Detector width: L_D
Input slit width: ω_{slit}



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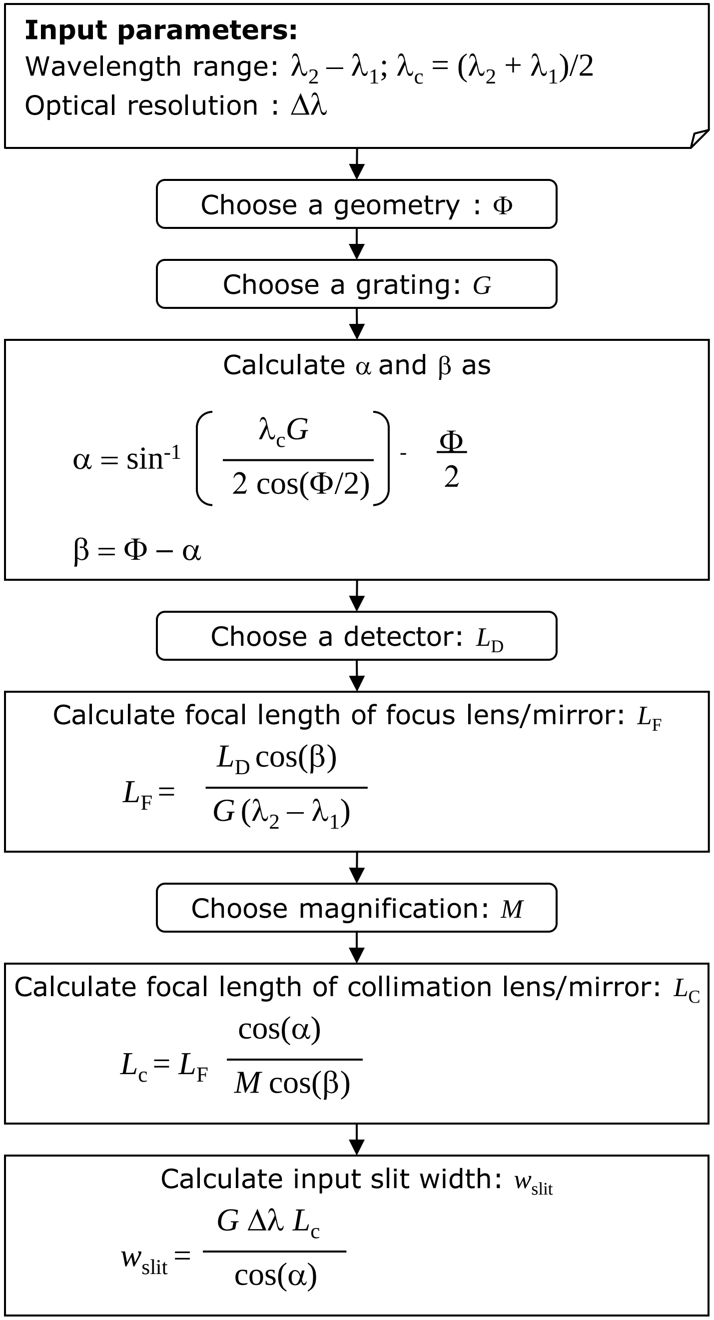

Input parameters:
Wavelength range: $\lambda_2 - \lambda_1$; $\lambda_c = (\lambda_2 + \lambda_1)/2$
Optical resolution : $\Delta\lambda$

Choose a geometry : Φ

Choose a grating: G

Calculate α and β as

$$\alpha = \sin^{-1}\left(\frac{\lambda_c G}{2\cos(\Phi/2)}\right) - \frac{\Phi}{2}$$

$$\beta = \Phi - \alpha$$

Choose a detector: L_D

Calculate focal length of focus lens/mirror: L_F

$$L_F = \frac{L_D \cos(\beta)}{G(\lambda_2 - \lambda_1)}$$

Choose magnification: M

Calculate focal length of collimation lens/mirror: L_C

$$L_c = L_F \frac{\cos(\alpha)}{M\cos(\beta)}$$

Calculate input slit width: w_{slit}

$$w_{slit} = \frac{G\,\Delta\lambda\,L_c}{\cos(\alpha)}$$

Step 1: Choose geometry

The first step is to choose among the Czerny-Turner or LGL type geometries. For the Czerny Turner a typical value for Φ is around 30° wheras transmission gratings are generally used in the Littrow configuration and –1st order where $\alpha = -\beta$ => Φ = 0°.

Step 2: Choose grating

The second step is to choose a diffraction grating. Most grating vendors have an on-line catalogue where you can find one or more grating options to try in your design. You should choose a grating that has high diffraction efficiency in your wavelength. The important parameter that you shall use for the design in the next steps is the groove density G.

Step 3: Calculate diffraction angle

The angle of incidence α on the grating and the diffraction angle β for the center wavelength λ_c are key parameters in the spectrometer design. These angles can be calculated once the grating groove density G and the total deflection Φ is chosen.

Step 4: Choose detector

The purpose of the spectrometer design is to disperse the wavelength range across the width of the detector array L_D. There are a large range of diode array detectors specifically designed for spectrometers. In general, if you need a compact spectrometer you should aim for a short detector (typically 1/4" or 6.4 mm). However, if you require a broad spectral range and/or a high resolution you should aim for a wide detector (typically 1/1" or 25.8 mm).

Step 5: Calculate focal length of focus lens

Once the width of the detector is know you can calculate the focal length of the focusing mirror/lens.

Step 6: Choose magnification

As mentioned earlier, the spectrometer is imaging the input slit to the detector and we generally want to have the slit as wide as possible to collect as much light through the input slit as possible. Therefore, the magnification in the system M should preferably be close to 1 which means that the width of the input slit ideally is imaged 1:1 onto the detector array.

Step 7: Calculate focal length of colli lens

As in any imaging system the magnification is determined by the ratio between the focal lengths of the two lenses in the system. For a spectrometer this ratio has to be slightly modified due to the defelction along the beam path in the grating. However, once the magnification is chosen the focal length of the collimation mirror/lens can easliy be calculated.

Step 8: Calculate input slit width

The input slit width ω_{slit} is determined by the required optical resolution Dl and the magnification. Once you know your input slit width you are ready to evaluate if your spectromete design is viable or you have to go back and change some of your choices for grating, detector, or magnification for instance.

Evaluation of design

Once you have done a design iteration using the 8 steps described in the previous pages you should check whether this design is practial at all. Three things that you can easily check are the **input slit width**, **diffraction limit of optics**, and **diffraction limit of grating** as described below.

Is the input slit width practical?

Input slits comes in widths down to 5 microns but such narrow slits will only allow very limited amount of light to enter your spectrometer. So, if your design requires a slit of 5 – 10 microns or less you could consider the following:

- loosening your requirement for the resolution
- choosing a wider detector and choosing a grating with a higher groove density

Diffraction limit of optics

The formulas on the previous pages does not take into account that the optics can never produce a spot smaller than the diffraction limit. You can use the following formula to calculate the FWHM in wavelength of the smallest possible spot your optics can produce:

$$\Delta\lambda_{\text{diffraction}} = 1.028 \frac{\lambda_c M (\lambda_2 - \lambda_1)}{2 L_D \tan(\theta_{NA})}$$

If this value is larger than your required $\Delta\lambda$, your system is diffraction limited by the optics and you will not be able to obtain a better resolution than $\Delta\lambda_{\text{diffraction}}$

Diffraction limit of grating

The grating itself does also have a diffraction limited spot size (referred to as resolving power of the grating). The more grating lines that are being illuminated ina grating the better the resolution of the grating. The following formula gives the FWHM in wavelength of the smallest possible spot your grating can produce:

$$\Delta\lambda_{\text{diffraction}} = 0.84 \frac{\lambda_c \cos(\alpha)}{2 G L_C \tan(\theta_{NA})}$$

If this value is larger than your required $\Delta\lambda$, your system is diffraction limited by the optics and you will not be able to obtain a better resolution than $\Delta\lambda_{\text{diffraction}}$