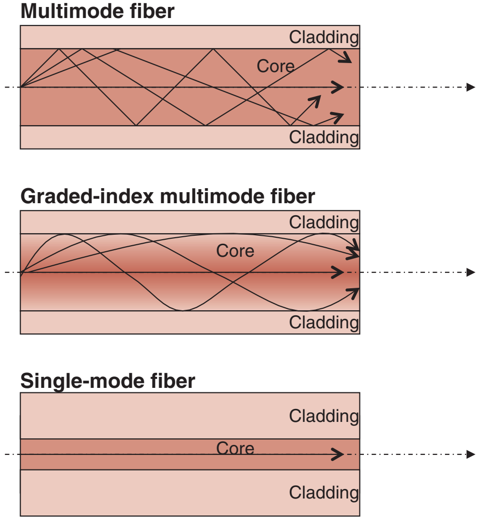
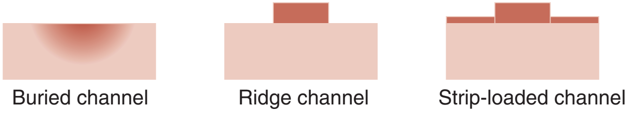
Optical Waveguide Types

There are two main types of **optical waveguide** structures: the step index and the graded index. In a **step-index waveguide**, the interface between the core and cladding is an abrupt change of index, producing the TIR effect. In a **graded-index waveguide**, the change between the core and cladding regions is smooth and continuous, therefore producing a refracted wave rather than a reflected wave. There are two types of step-index waveguides: multimode and monomode (single mode). Only a single mode can propagate in the latter, whereas a multitude of modes (TIR-reflected angles) can propagate in the former.



When light is confined by coatings rather than by TIR, it may be referred to as a **light pipe** rather than a waveguide. Optical **planar waveguides** come in various types, including buried channel guide (graded index), ridge or strip-loaded channel guide (step index), or even photonic crystal (PC) waveguide (holey fiber).

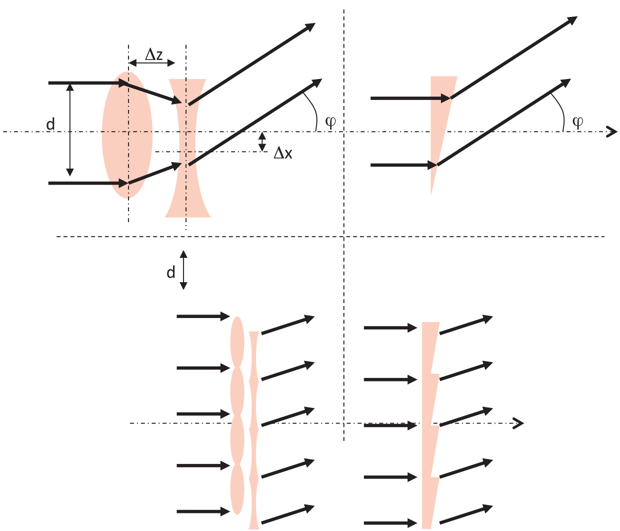


Beam Steering with MLAs

Beam steering with MLAs is a useful way to steer an incoming beam by laterally moving one MLA with regard to the other (e.g., an afocal inverted telescope). The following figure shows one such MLA system and its resulting prism counterpart. The same principle can be applied to arrays of such lenses in order to produce a thin but large area to be steered, when thickness is essential. However, care must be taken with parasitic crosstalk between neighboring lenses. The resulting deflection angle for a typical dual-MLA beam-steering system is given by

$$\varphi = -\arctan\left(\frac{\Delta x}{d f\#}\right)$$

where *f*# is the *f*-number of the lens, and Δx is the relative lateral MLA displacement.



Small lateral offsets can produce large angular deflections. When aligned, such arrays are also known as afocal angle enlargers, enlarging the incoming beam angle by the magnification ratio of the MLA system. If the MLAs are diffractive, spectral dispersion and diffraction efficiency must be addressed. Angular shifts of tens of degrees can be achieved by micrometric lateral shifts.

Athermalizing Hybrid Lenses

Athermalization can be achieved in a hybrid singlet in a way similar to that of achromatic singlets (thermal spectral drifts have opposite signs in refractives and diffractives, similar to spectral dispersion characteristics).

- The **optothermal expansion coefficient** x_{ref} for a refractive lens of focal length f, curvature c, and index n can be written as

  $$f = \frac{1}{(n-1)c} \Rightarrow x_{f,\text{ref}} = \left(\frac{1}{f}\right)\frac{\partial f}{\partial T} \approx \left(\frac{1}{n-1}\right)\frac{\partial n}{\partial T}$$

  The focal-length variation for a diffractive lens as a function of the temperature is given by

  $$f(T) = \frac{n_0 r_m^2}{2m\lambda_0} = \frac{1}{2m\lambda_0} r_m^2 (1 + \alpha_g \Delta T)^2 n_0$$

- The optothermal expansion coefficient x_{dif} for a diffractive lens can be written as

  $$x_{f,\text{dif}} = \left(\frac{1}{f}\right)\frac{\partial f}{\partial T} \approx 2\alpha_g + \left(\frac{1}{n_0}\right)\frac{\partial n_0}{\partial T}$$

  Inverse to spectral dispersion, the amplitude of the thermal expansion of diffractives is much smaller than the amplitude of the thermal expansion of refractives: $|x_{f,\text{dif}}| << |x_{f,\text{ref}}|$.

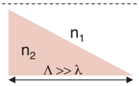
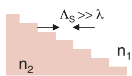
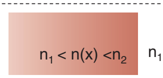
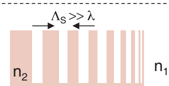
By equating both values, it is therefore possible to design an athermal lens (a hybrid singlet refractive/diffractive athermal lens) in which the focal length does not vary with temperature as it would for individual refractive or diffractive lenses: $x_{f,\text{doublet}} = x_{f,\text{mount}}$.

Although a typical hybrid achromatic singlet lens would have most of the power on the refractive surface, a typical hybrid athermal singlet will have most of the power on the diffractive surface. This makes it difficult to design and fabricate hybrid refractive/diffractive lenses that are simultaneously achromatic and athermal.

Effective Medium Theory (EMT)

When the minimum period becomes smaller than the reconstruction wavelength, the incoming light does not reach the structures but rather "sees" an analog effective index modulation that is produced by the subwavelength (usually binary) structures.

The following table shows an example of a blazed grating profile (local phase ramp) that is physically implemented by various techniques (analog or multilevel surface ramp, real index modulation, and effective index ramp through binary subwavelength structures).

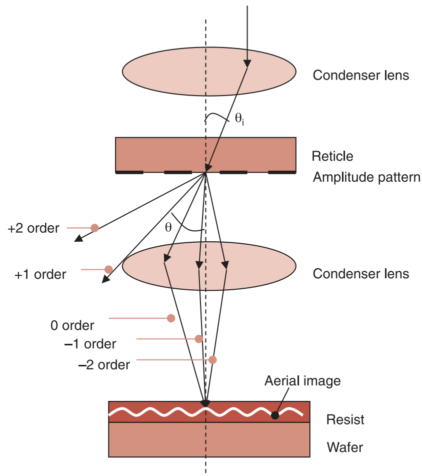
Physical aspect	Comments
	A) Continuous profiles
	B) Multi-level approximation -> multi-mask process
	C) Effective medium approach
	D) Single-step planar (binary) technology

In this example, the smooth phase profile producing the blaze is implemented as a **pulsewidth modulation** (PWM) along each period of the grating. The structures are fabricated over a regular grid, and each structure is slightly smaller, producing a linearly varying sub-grating duty cycle. Note that one can also use a **pulse-density-modulation** (PDM) scheme or even an error-diffusion algorithm, such as the one used in greyscale laser printing.

Because there is only a single etch depth for EMT structures, a single lithography and etching step is required. However, the resulting element behaves as a multilevel or quasi-analog surface-relief element. This is thus an efficient fabrication technique when compared to systematic errors (alignment, etch) that occur in multilevel lithography.

Step-and-Repeat Lithography

Steppers are high-resolution tools that use reticles at 10×, 5×, or 4× magnification, but they can only print small fields, such as 20 × 20 mm, typically. When the elements to be printed are larger than that field, a mask-aligning lithography tool (1× system) must be used.



Various stepper systems currently exist with increasingly smaller illumination wavelengths. A stepper can be one to two orders more expensive than a mask aligner, but it can produce much-smaller features, though on a smaller field. Yesterday's I-line steppers can go below 0.5 μm, today's deep UV (DUV) steppers can go below 100 nm, and tomorrow's extreme UV (EUV) steppers go below 10 nm.

Year	Source	Type	λ (nm)	NA	k_1	δ*x* (μm)
1980	Mercury arc lamp	G line	436	0.28	0.96	1.50
1983				0.35	0.96	1.20
1986		H line	405	0.45	1.00	1.00
1989		I line	365	0.45	0.86	0.70
1992				0.54	0.74	0.50
1995				0.60	0.57	0.35
1997	UV laser	KrF	248	0.93	0.50	0.25
1999				1.00	0.43	0.18
2001				0.75	0.37	0.11
2003	DUV laser	ArF	193	0.85	0.45	0.09
2005		F_2	157	0.90	0.45	0.06
2008	EUV	X ray (R&D)	13	0.20	0.50	0.03