Astrophotonics

Experimental Astrophysics (PHYS1901)

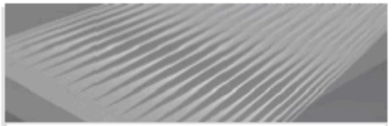
J. Bland-Hawthorn

University of Sydney

2014

Molding the flow of light: photonics in astronomy

Joss Bland-Hawthorn and Pierre Kern



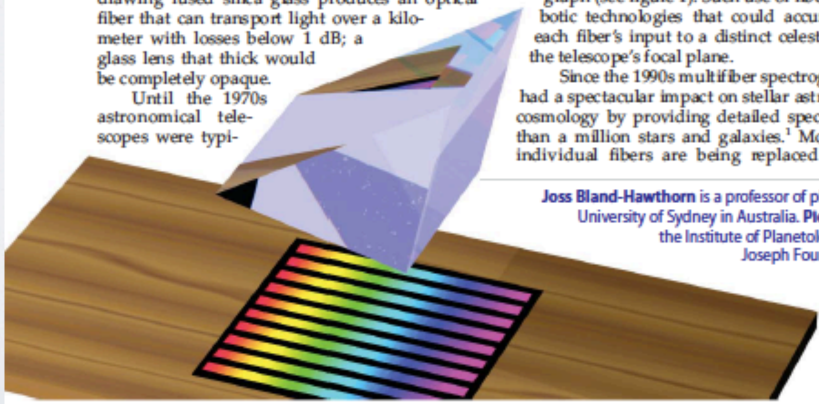
Light gathered and focused by a telescope must often be refocused onto spectrographs and other complex instruments. To such ends, astronomers are coming to realize the benefits of photonics.

Modern astronomy began with the invention of the telescope by Hans Lippershey in 1608 and its prompt appropriation by Galileo. From small beginnings, the largest optical telescopes today have mirror diameters in excess of 10 meters. By the end of this decade, one or more of a new generation of extremely large telescopes (ELTs) will begin to scan the heavens. But the ability to focus light is only part of the problem. Once concentrated, the light must be refocused into a modern telescope's complex instruments, where it is dissected and analyzed.

Photonics has been described as "molding the flow of light." An early demonstration of what we now understand as photonics dates back to 1841, when Jean-Daniel Colladon in Geneva showed how a thin parabolic jet of water falling under gravity guides light along its length. But the use of photonics in astronomy had to await the invention of high-quality optical fibers around 1970. Even then, it took a decade before instrument builders fully realized their potential. It is remarkable that the process of drawing fused silica glass produces an optical fiber that can transport light over a kilometer with losses below 1 dB; a glass lens that thick would be completely opaque.

Until the 1970s astronomical telescopes were typically used just to concentrate the light from one celestial source at a time. But astronomers realized that optical fibers could be used to observe many celestial sources at once—one fiber for each source. One end of each fiber is aligned with an individual source, and the other end illuminates a spectrograph (see figure 1). Such use of fibers led to robotic technologies that could accurately align each fiber's input to a distinct celestial object at the telescope's focal plane.

Since the 1990s multifiber spectrographs have had a spectacular impact on stellar astronomy and cosmology by providing detailed spectra of more than a million stars and galaxies.[1] More recently, individual fibers are being replaced by closely

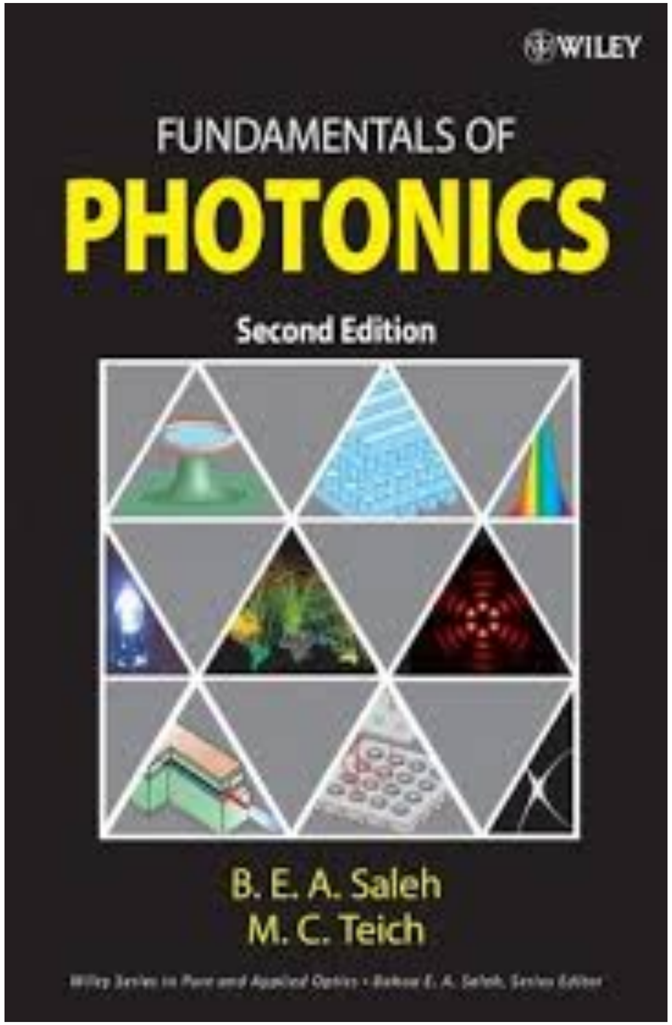


Joss Bland-Hawthorn is a professor of physics and federation fellow at the University of Sydney in Australia. **Pierre Kern** is a research engineer in the Institute of Planetology and Astrophysics of CNRS and Joseph Fourier University in Grenoble, France.

Main photonics text (supplied)

7: Guided wave optics
(Ch. 8 in 2nd edition)

8: Fibre optics
(Ch. 9 in 2nd edition)

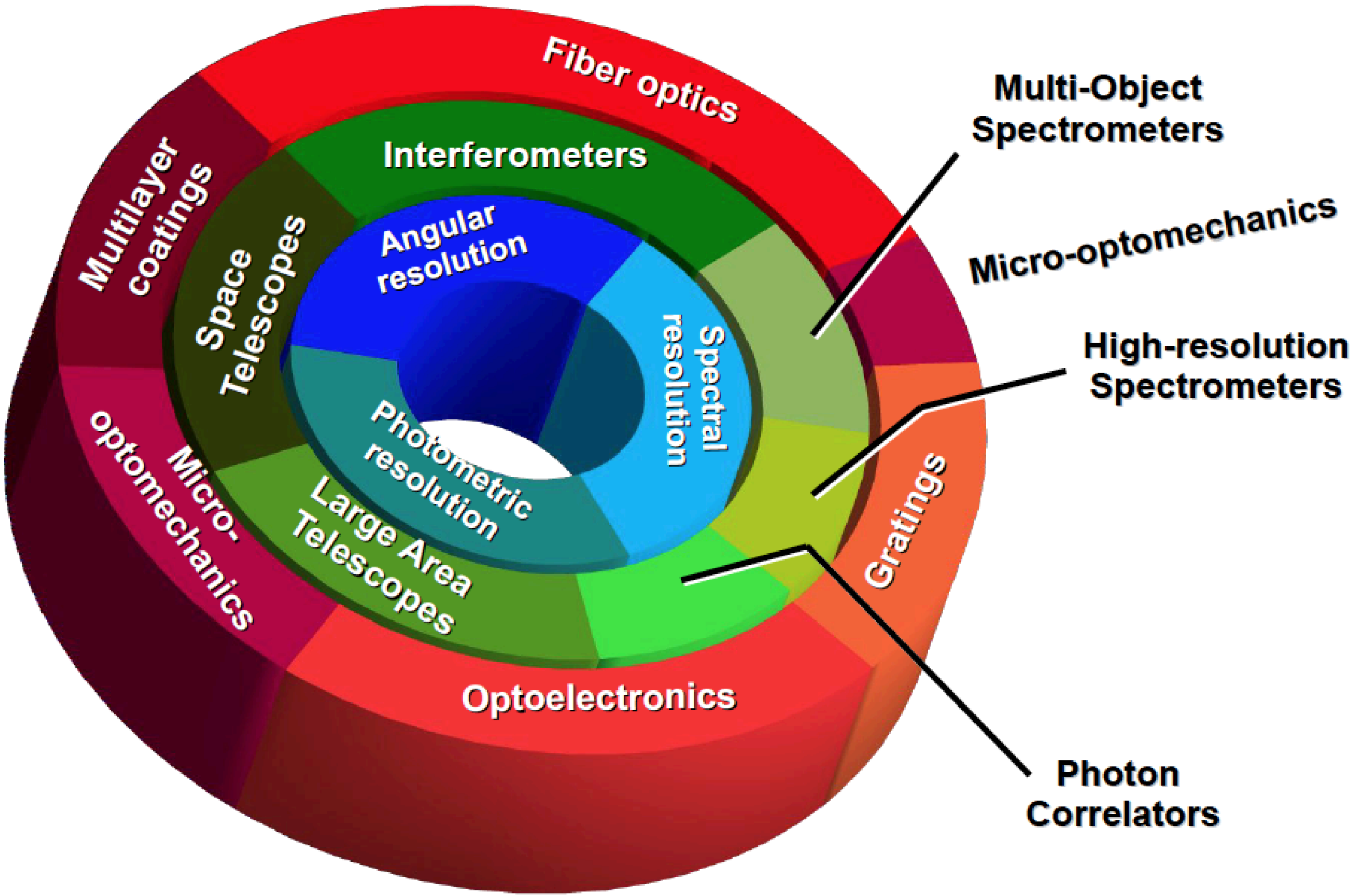


What is observational astronomy?

Define electric field $E(\vec{x},t)$ then intensity is $E^*.E$

Bolometry	$E^*(0,0).E(0,0)$
Spectroscopy	$E^*(0,0).E(0,t)$
Interferometry	$E^*(0,0).E(x,0)$
Spectro-interferometry	$E^*(0,0).E(x,t)$

What lies beyond? *Recall that this is all single photon statistics.*


Fiber optics
Interferometers
Multilayer coatings
Space Telescopes
Angular resolution
Spectral resolution
Photometric resolution
Large Area Telescopes
Micro-optomechanics
Optoelectronics
Gratings
Multi-Object Spectrometers
Micro-optomechanics
High-resolution Spectrometers
Photon Correlators

What is photonics ?

- Many overlapping fields now:

optics, optoelectronics, nonlinear optics, quantum optics, microoptics, photonics, nanophotonics, electro-optics, quantum electronics, lightwave technology, …

- Photonics is manipulation of light in materials:

what it means in practice is still evolving, e.g. optoelectronics and nonlinear optics are being subsumed and redefined

Why photonics ?

- Many new ways to manipulate light → new science
- Leveraging huge investment in telecom industry
- Increasing sophistication in instrument design (e.g. Gravity)
- Size reduction, mass replication, cost reduction
- Breaking the mold of huge monolithic instruments
- Following industrial trends, evolution in physics (nanoscales)

Photonic functions

1D → 3D photonic waveguides

Switching, masking, reformatting

Dispersing, filtering, tuning

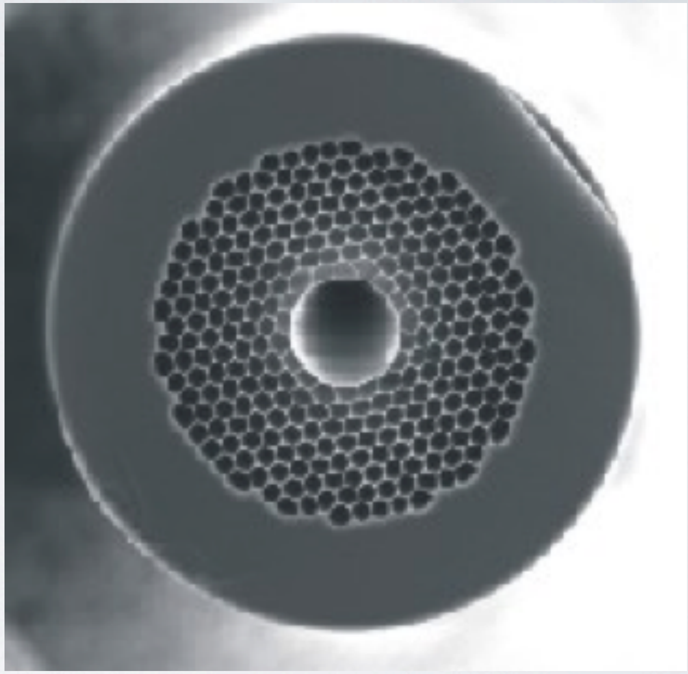
Chirping, timing

Beam conversion, shaping, splitting

Beam merging, switching, steering

Beam polarizing

Interferometry, metrology, sensors…



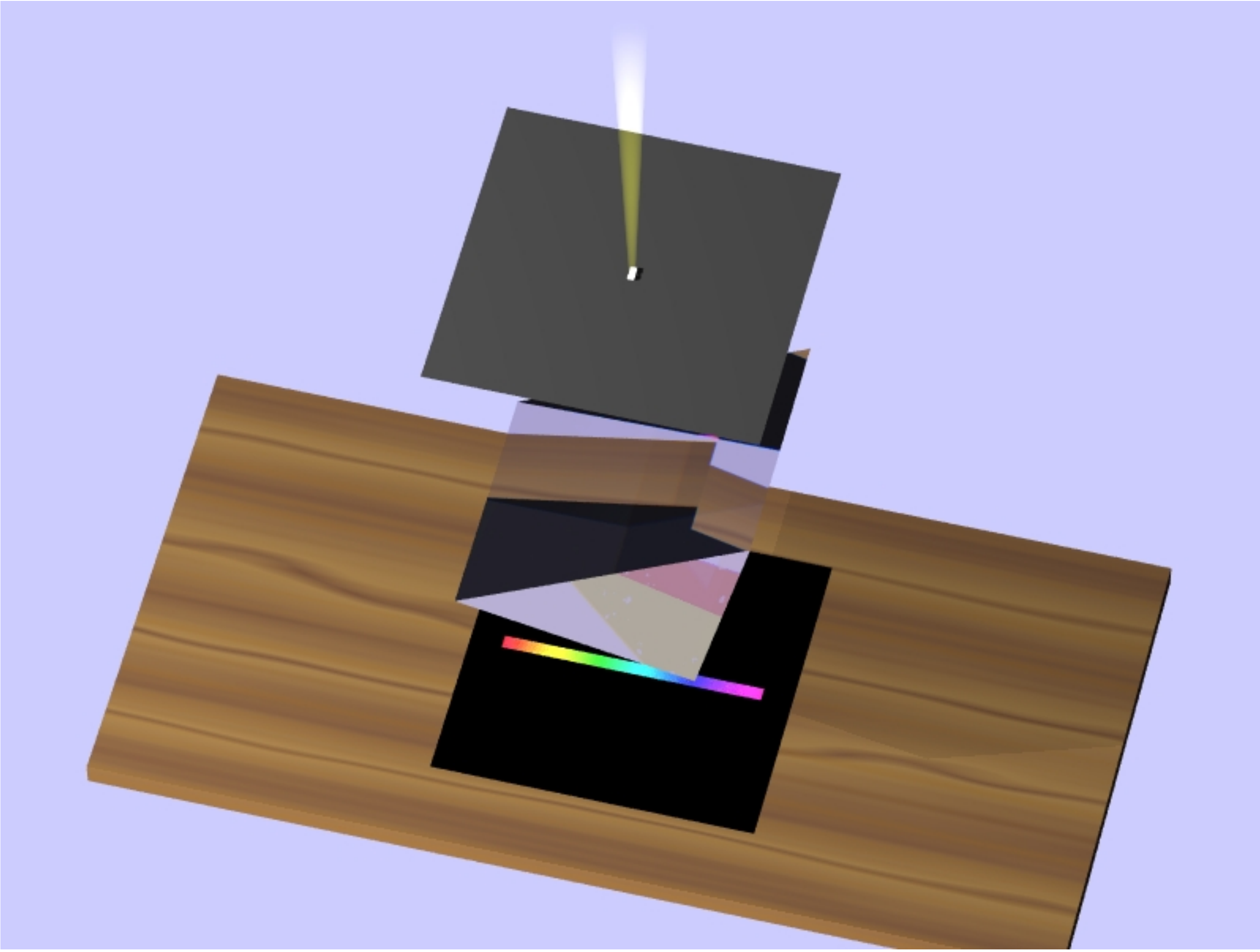
1980 forwards

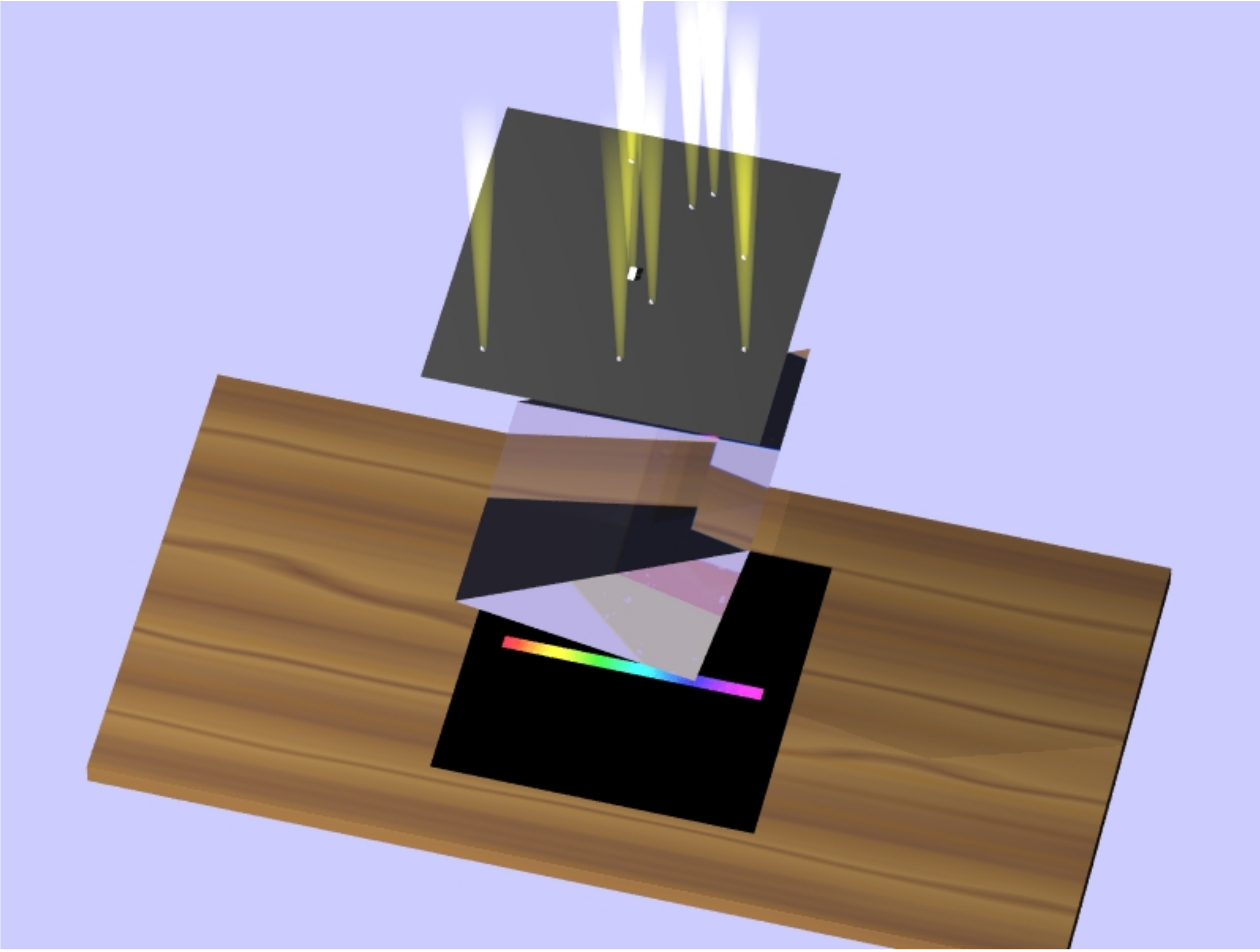
2009 Nobel Prize in Physics
Charles Kao (HK) jointly with
Boyle & Smith for the CCD

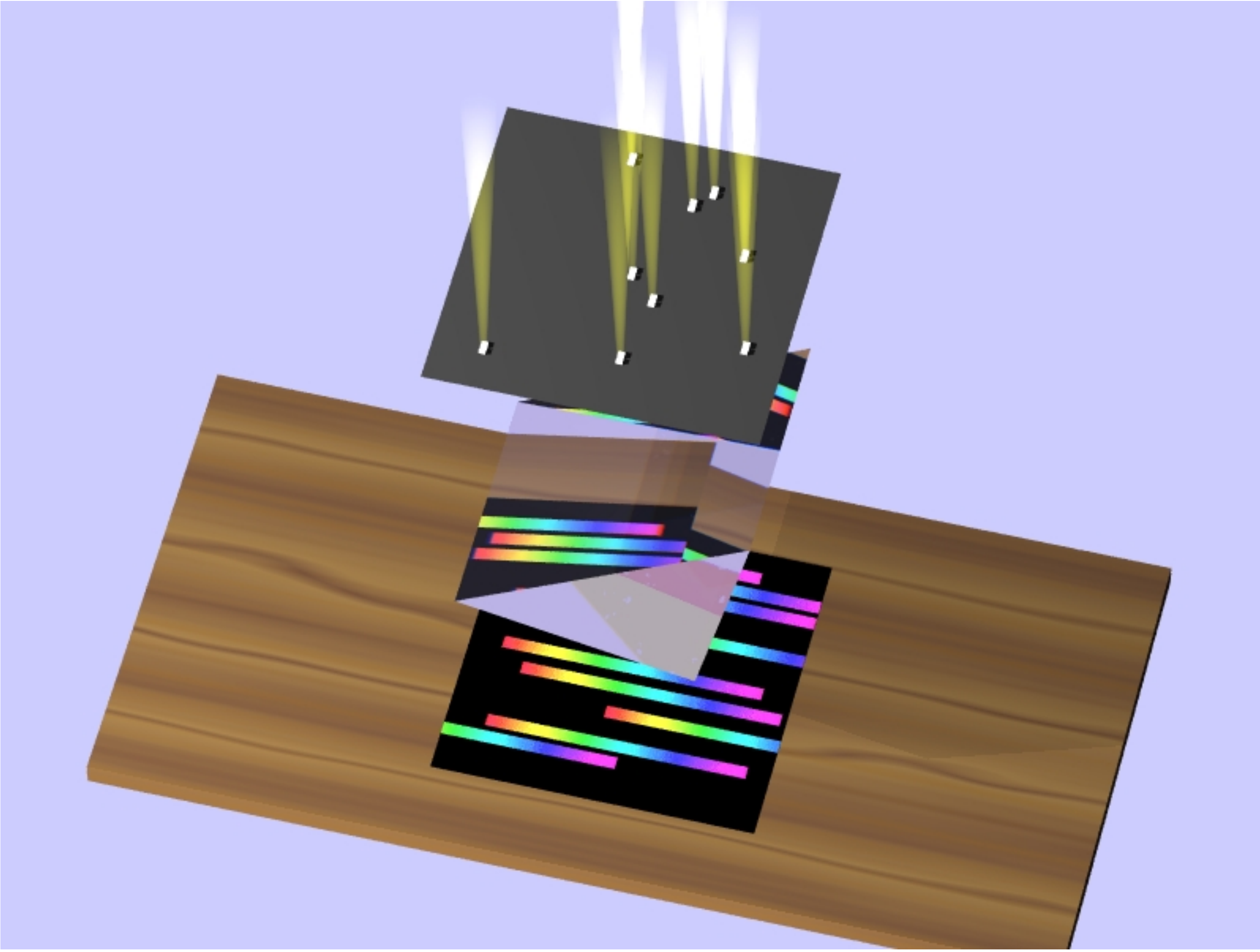
- High quality optical fibres for light transport
- Exploit widest possible focal plane field
- Reformat spectra efficiently over detector
- The rise of robotic positioners and huge galaxy & stellar surveys

I start with the simplest application of photonics. By the last lecture, we will see incredibly sophisticated photonic instruments, e.g. ESO's VLTi, Gravity, etc. far beyond anything you could pull off with conventional optics.

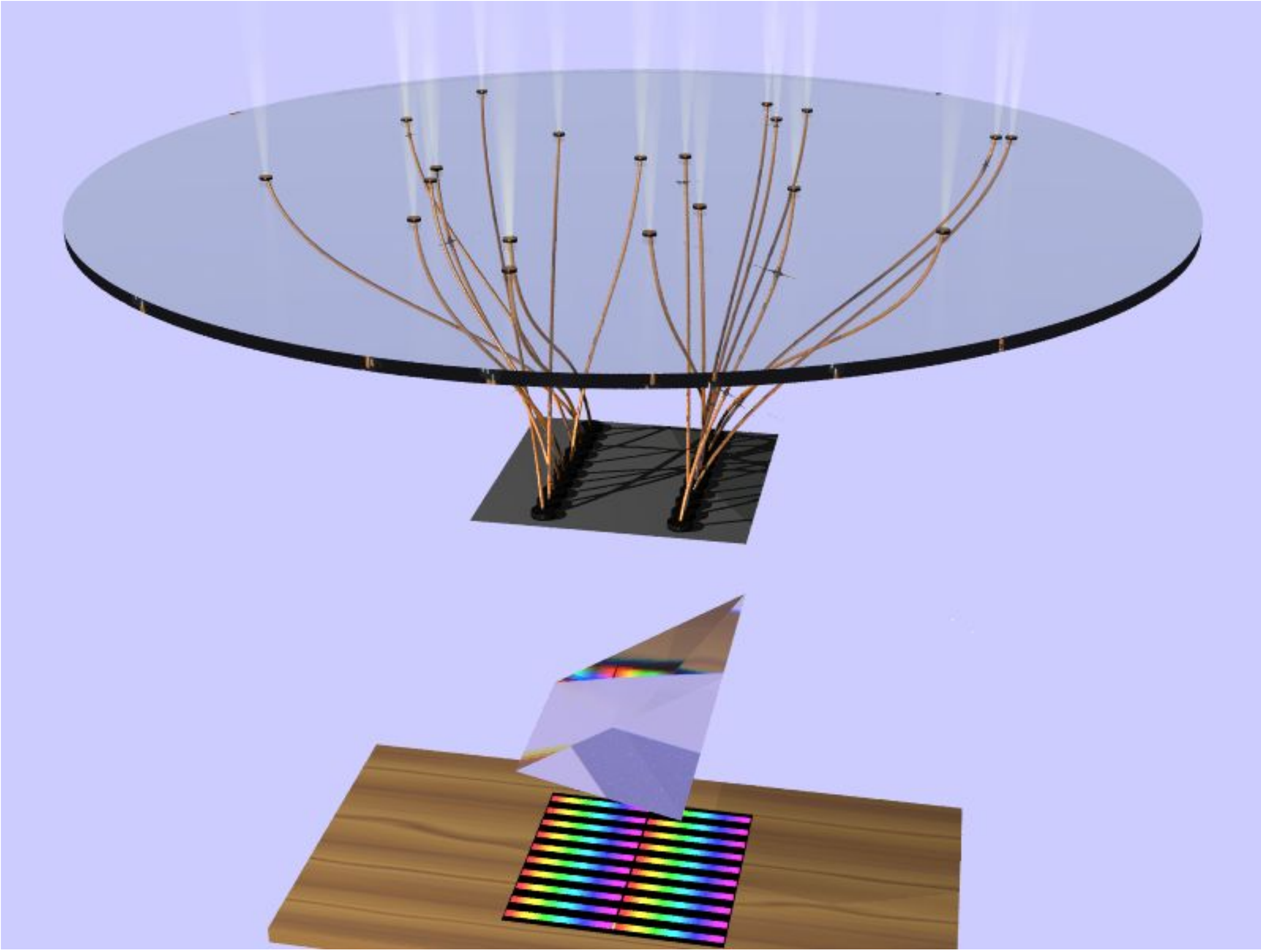
Sources used to be observed one at a time







Wide field – robotic positioning – packed detector



I will focus the 4 lectures on key developments…

Fibres, bundles

Multicore fibres

Photonic lanterns, solid lanterns, dicers

Fibre Bragg gratings

Waveguides, array waveguides

Laser combs

Ring resonators

Optical vortex generation, OAM

Optical circulators

Raman spectroscopy

…. relevant to our developments

Ground-based telescope instrumentation: astronomy
(e.g. GNOSIS, PRAXIS, SAMI, Hector, PIMMS, VAMPIRES, Dragonfly)

Space-based instrumentation: remote sensing
(e.g. nanoSPEC, i-INSPIRE)

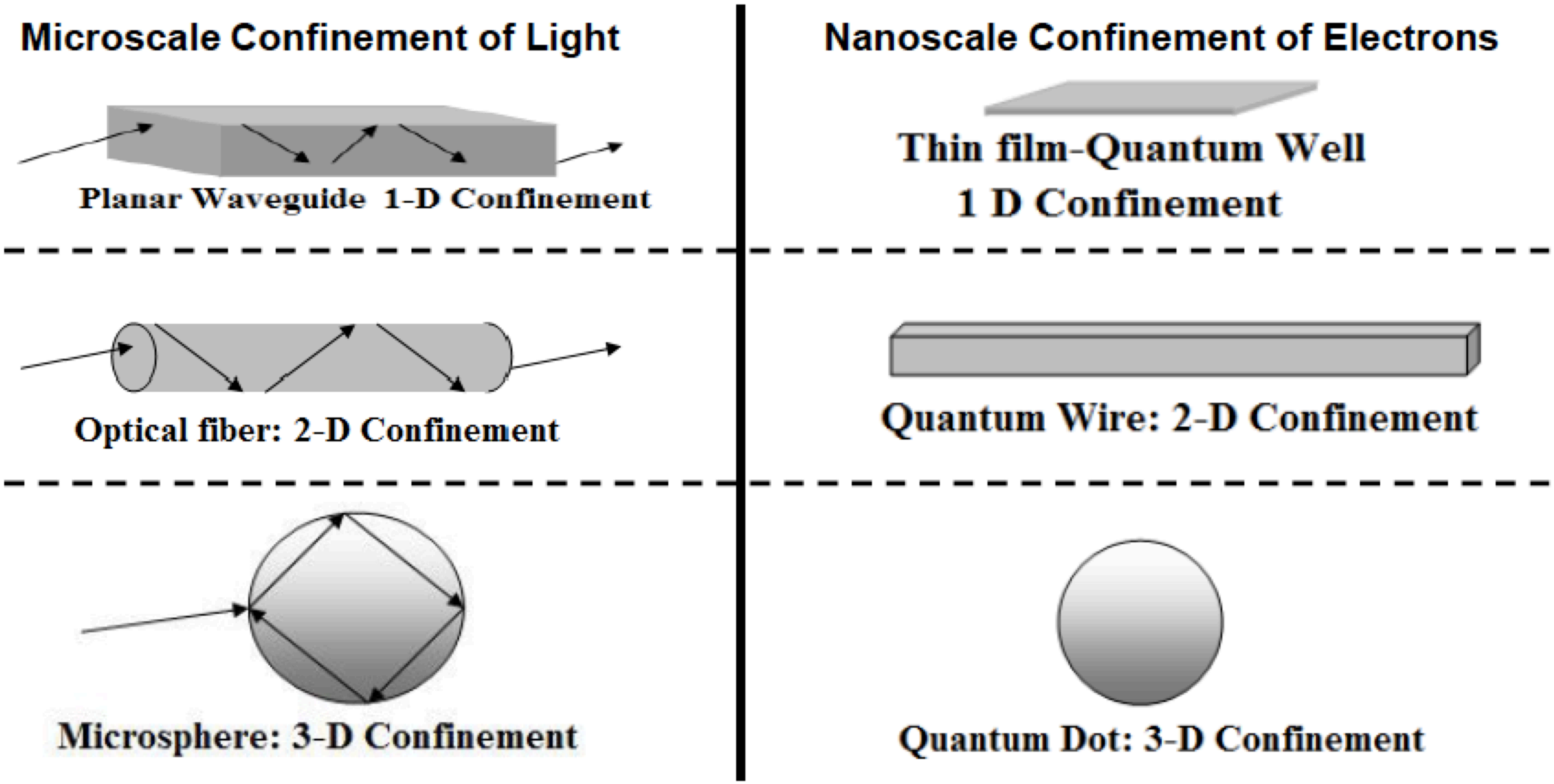
Telecomms: multicore grating filters, mode switching
(e.g. Alcatel Lucent, CUDOS)

Food safety: Raman spectroscopy (pulsed)
Medical physics: Raman spectroscopy
(e.g. AusVeg, HAL, Charles Perkins Centre)

All of these tell a story – I only have time to cover some classical theory and a few applications that embody the principles of astrophotonics.

Photonics is microscale – important analogy with nanoscale

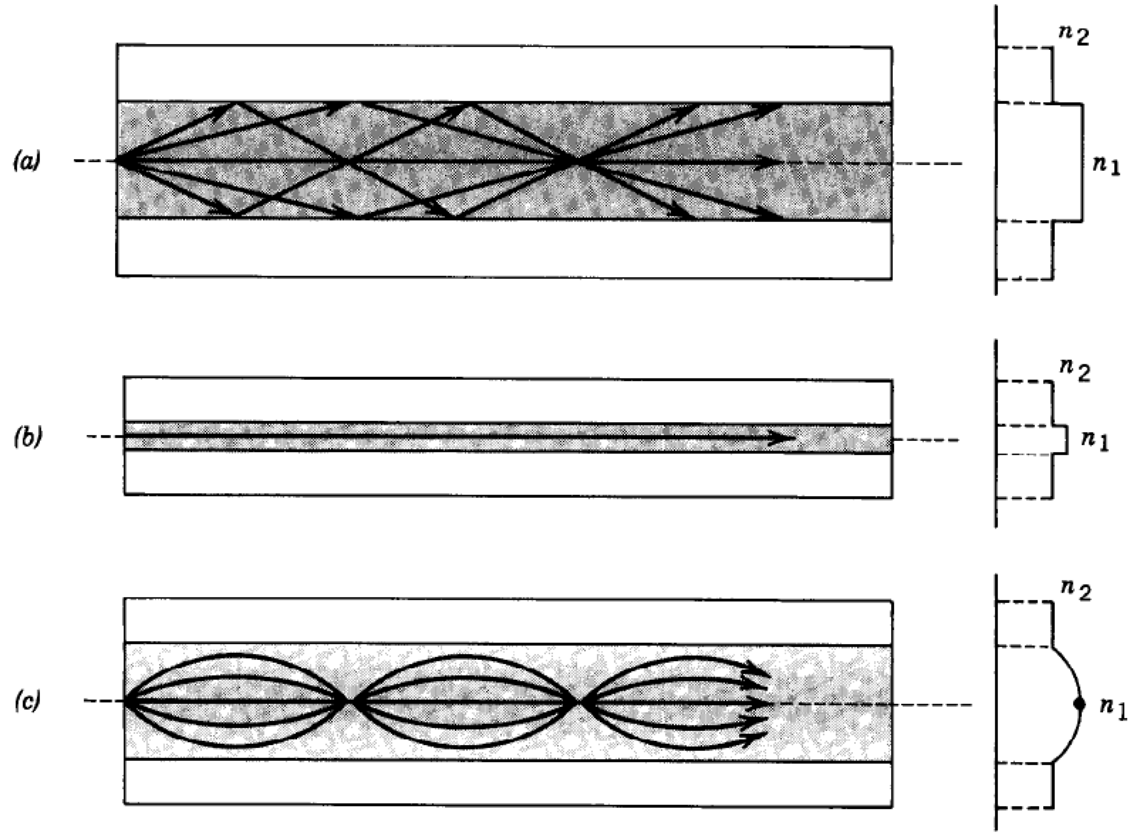
Confinement of Light results in field variations similar to the confinement of Electron in a Potential Well. For Light, the analogue of a Potential Well is a region of high refractive-index bounded by a region of lower refractive-index.



A deep understanding of photonics requires more familiarity with quantum processes on nanoscales than optical processes on microscales, say 2:1 ratio for the sake of argument.

Optical fibres:

Guiding, losses, properties



MMF

SMF

GRIN

Figure 8.0-2 Geometry, refractive-index profile, and typical rays in: (*a*) a multimode step-index fiber, (*b*) a single-mode step-index fiber, and (*c*) a multimode graded-index fiber.

Cylindrical dielectric waveguide, fused silica glass (SiO_2) of high chemical purity.
Small changes in *n* using dopants (e.g. Ti, Ge, Bo).

Operates by total internal reflection: outer "cladding" has lower *n* than inner "core."

NUMERICAL APERTURE (*NA*)

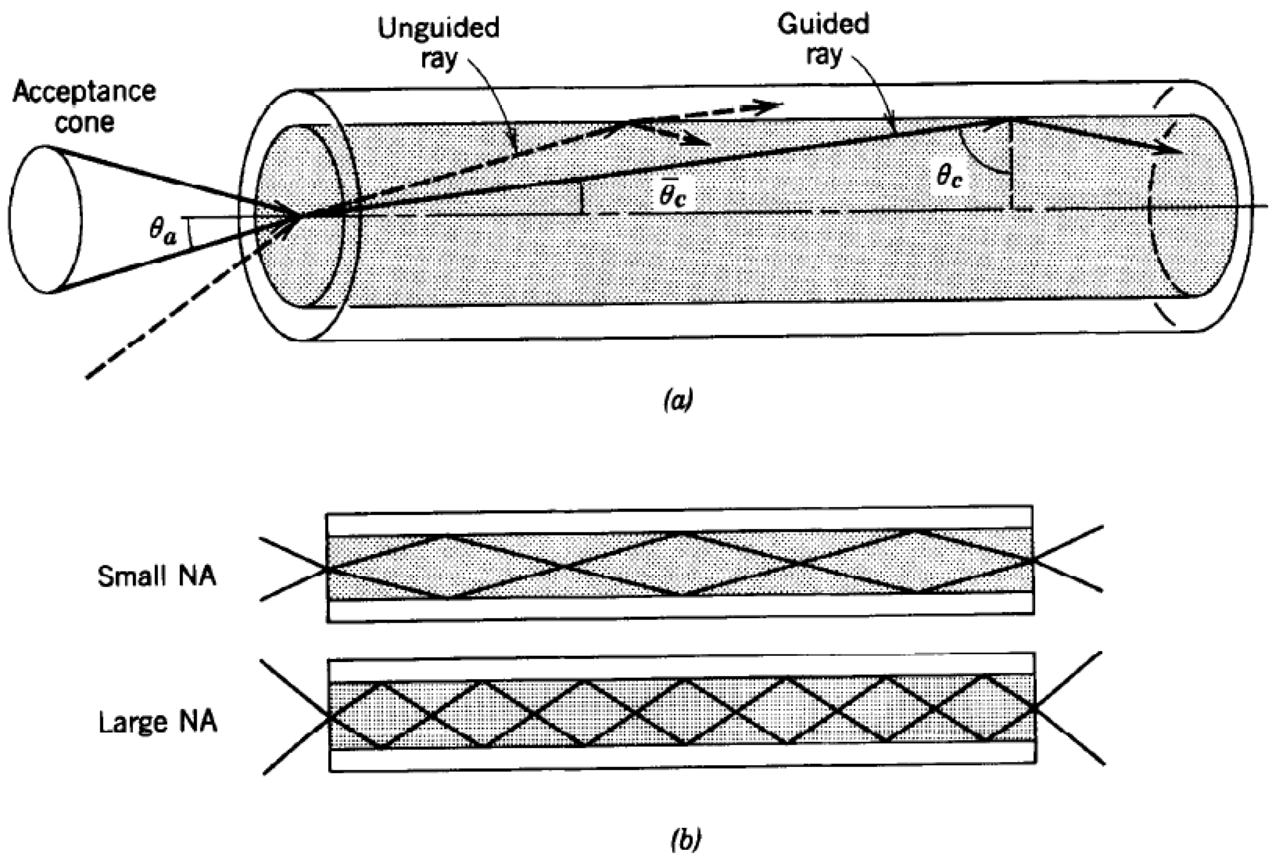
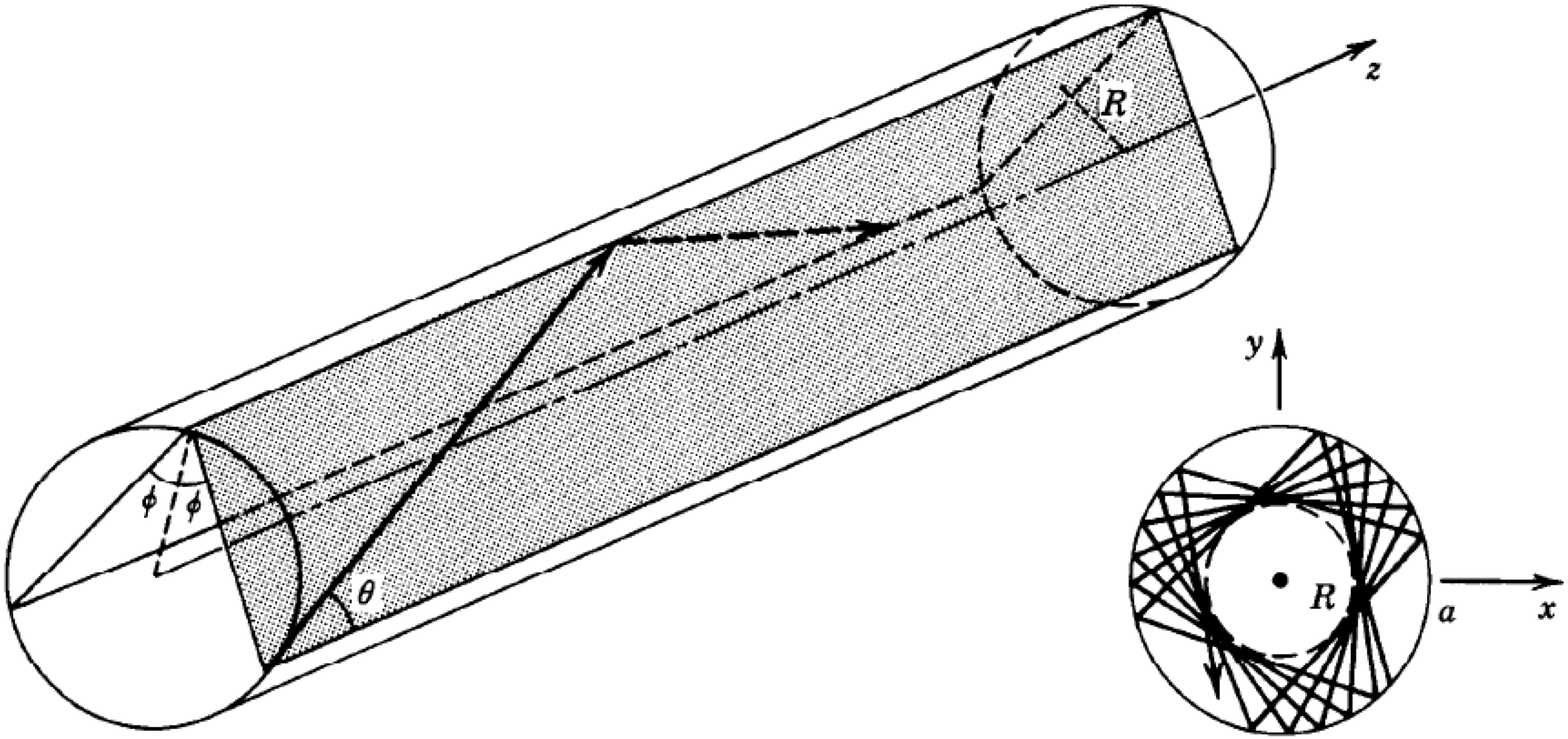


Figure 8.1-3 (*a*) The acceptance angle θ_a of a fiber. Rays within the acceptance cone are guided by total internal reflection. The numerical aperture NA = sin θ_a. (*b*) The light-gathering capacity of a large NA fiber is greater than that of a small NA fiber. The angles θ_a and $\bar{\theta}_c$ are typically quite small; they are exaggerated here for clarity.

$$NA = \sin\theta_a = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}$$

$$\Delta = \frac{n_1 - n_2}{n_1}$$



The ray analogy is of limited use - much of the energy moves in azimuth, i.e. missing the optical axis. Fibres are fantastic at scrambling information in azimuth; scrambling in radius is far harder, hence the **scrambling problem** you may have heard about in the context of planet hunting spectroscopy. (Polarization-maintaining fibres do exist.)

WAVE PROPAGATION

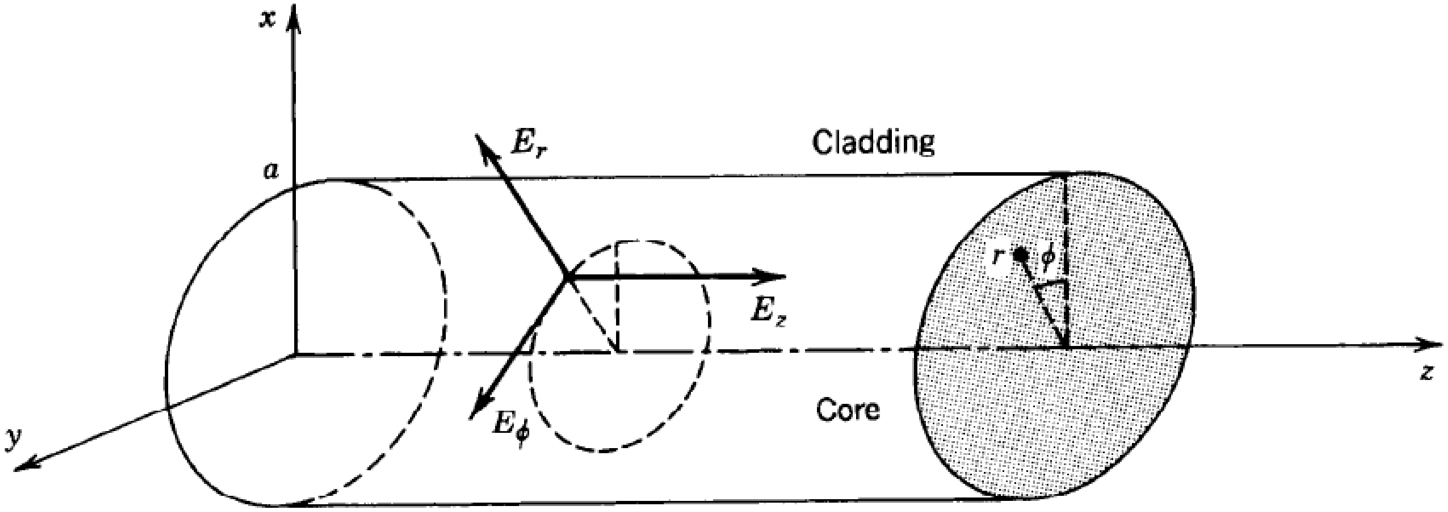


Figure 8.1-4 Cylindrical coordinate system.

Helmholtz Equation – just a wave equation with partial derivatives to account for 3D nature of problem $U(r, \varphi, z)$.

$$\frac{\partial^2 U}{\partial r^2} + \frac{1}{r}\frac{\partial U}{\partial r} + \frac{1}{r^2}\frac{\partial^2 U}{\partial \phi^2} + \frac{\partial^2 U}{\partial z^2} + n^2 k_o^2 U = 0$$

Both of these quantities are referred to as wavenumbers, but the lower is preferred because it has the units of the propagation constant β

$$k_0 = 2\pi / \lambda_0$$

$$nk_0 = 2\pi n / \lambda_0$$

The guided modes are waves travelling in z with propagation constant β such that $U(z) \propto \exp(-i\beta z)$.

The modes are periodic in φ such that $U(\varphi) \propto \exp(-i\, l\, \varphi)$, for which l integer.

$$U(r, \phi, z) = u(r) e^{-jl\phi} e^{-j\beta z}, \qquad l = 0, \pm 1, \pm 2, \ldots,$$

The Helmholtz equation easily reduces to

$$\frac{d^2u}{dr^2} + \frac{1}{r}\frac{du}{dr} + \left(n^2 k_o^2 - \beta^2 - \frac{l^2}{r^2}\right) u = 0.$$

For the core/cladding to guide

$$n_2 k_0 < \beta < n_1 k_0$$

We define coefficients in the cladding and core, respectively

$$\gamma^2 = \beta^2 - n_2^2 k_o^2, \quad k_T^2 = n_1^2 k_o^2 - \beta^2$$

$$\frac{d^2u}{dr^2} + \frac{1}{r}\frac{du}{dr} + \left(k_T^2 - \frac{l^2}{r^2}\right)u = 0, \qquad r < a \text{ (core)},$$

$$\frac{d^2u}{dr^2} + \frac{1}{r}\frac{du}{dr} - \left(\gamma^2 + \frac{l^2}{r^2}\right)u = 0, \qquad r > a \text{ (cladding)}.$$

k_T^2 and γ^2 are positive and the coefficients are real. Famous bounded solutions in terms of the Bessel function J and modified Bessel function K, i.e. oscillating functions with decaying amplitudes. K allows for central hole.

$$u(r) \propto \begin{cases} J_l(k_T r), & r < a \text{ (core)} \\ K_l(\gamma r), & r > a \text{ (cladding)}, \end{cases}$$

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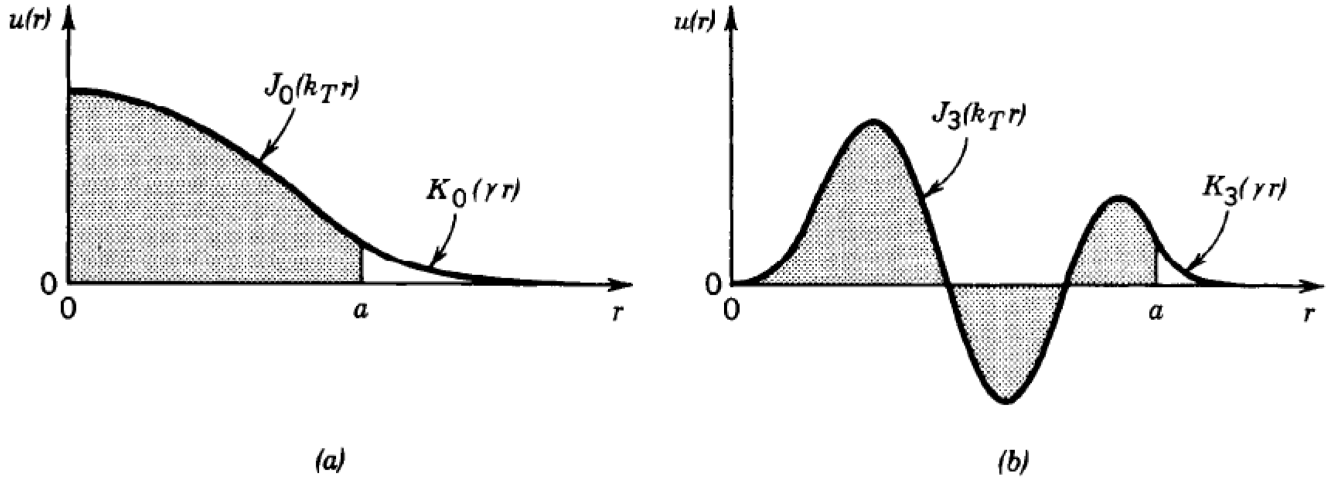


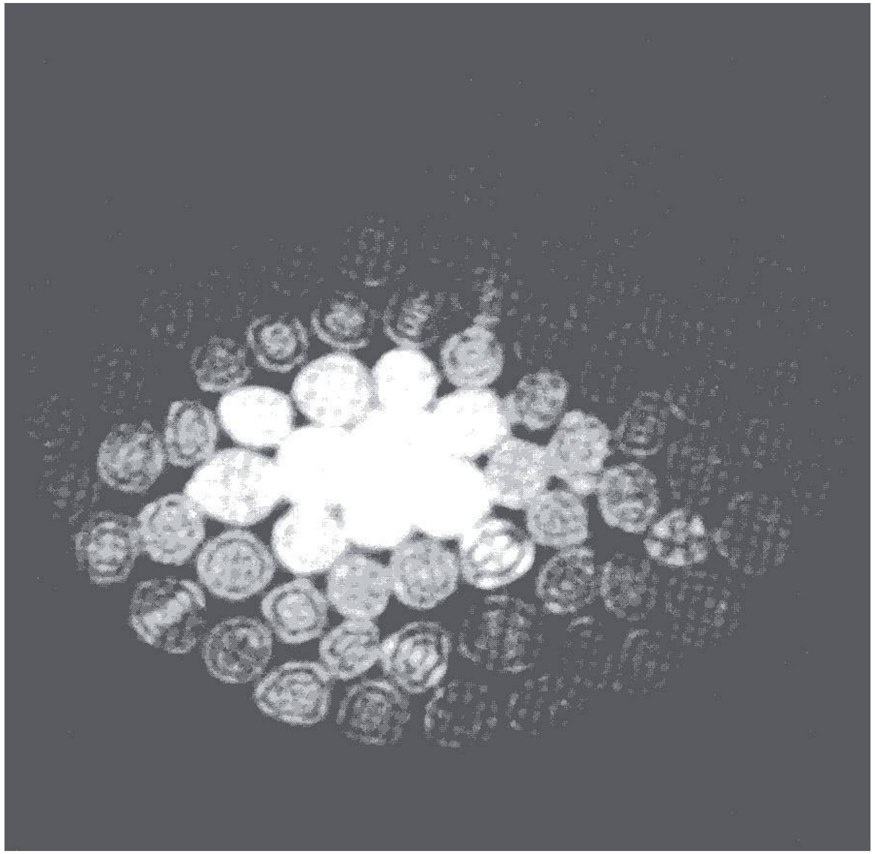
Figure 8.1-5 Examples of the radial distribution $u(r)$ given by (8.1-9) for (*a*) $l = 0$ and (*b*) $l = 3$. The shaded areas represent the fiber core and the unshaded areas the cladding. The

$$k_T^2 + \gamma^2 = (n_1^2 - n_2^2)k_o^2 = \mathrm{NA}^2 \cdot k_o^2, \qquad (8.1\text{-}11)$$

so that as k_T increases, γ decreases and the field penetrates deeper into the cladding. As k_T exceeds $\mathrm{NA} \cdot k_o$, γ becomes imaginary and the wave ceases to be bound to the core.

Optical waveguide mode patterns

Optical waveguide mode patterns seen in the end faces of small diameter fibers



Optics-Hecht & Zajac Photo by Narinder Kapany

Multimode propagation

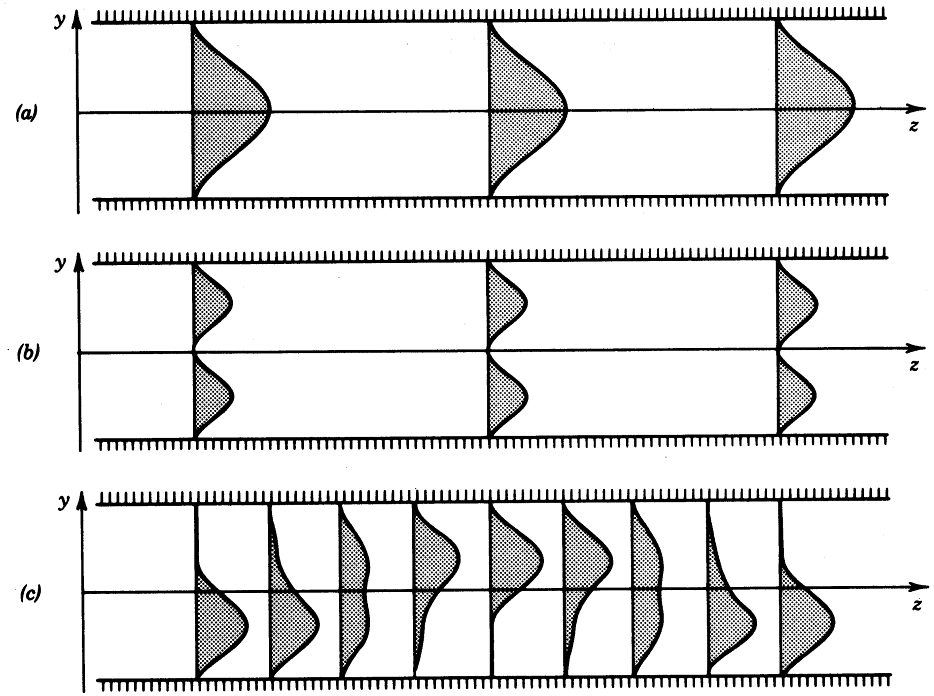
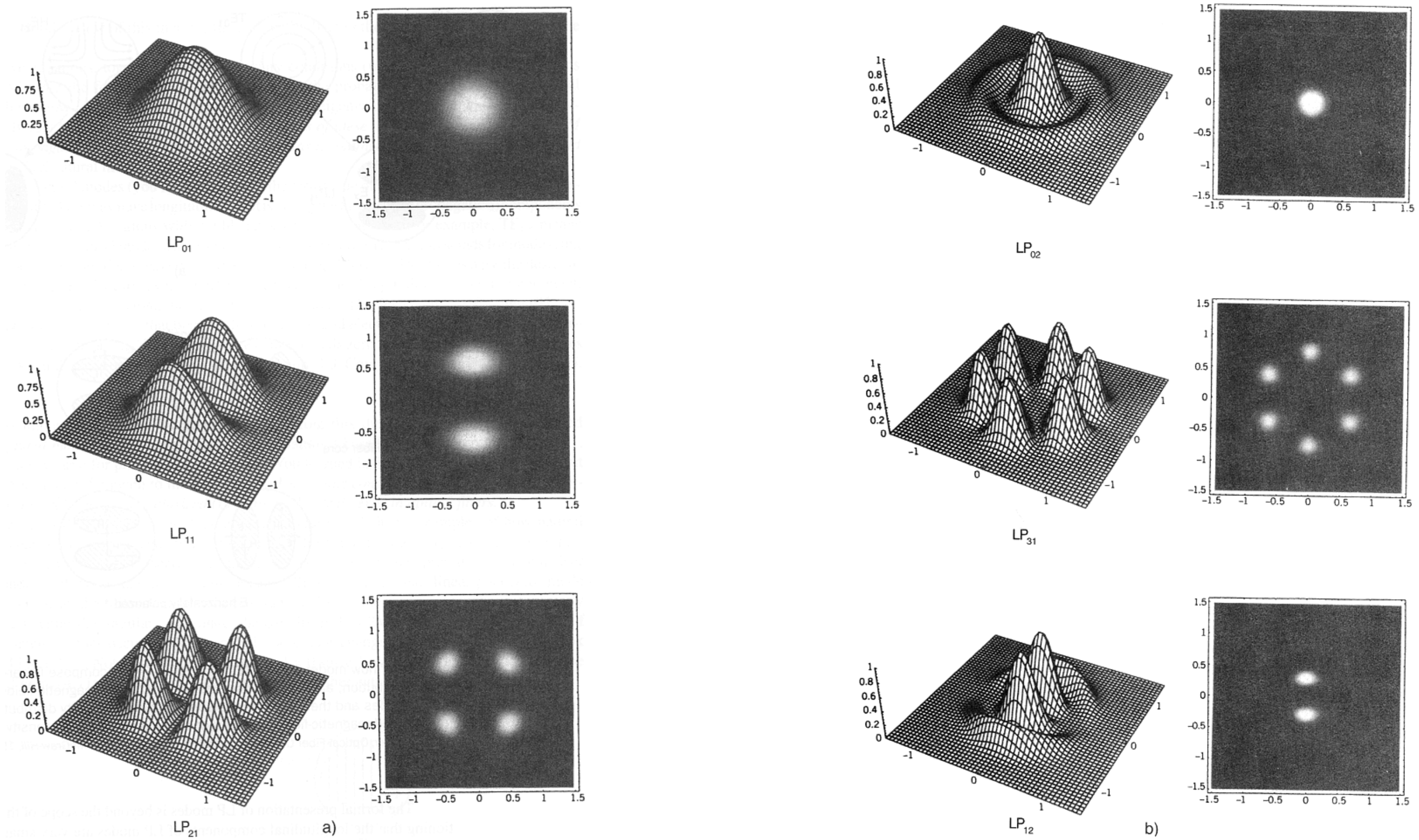


Figure 7.1-8 Variation of the intensity distribution in the transverse direction y at different axial distances z. (a) The electric-field complex amplitude in mode 1 is $E(y, z) = u_1(y)\exp(-j\beta_1 z)$, where $u_1(y) = \sqrt{2/d}\cos(\pi y/d)$. The intensity does not vary with z. (b) The complex amplitude in mode 2 is $E(y, z) = u_2(y)\exp(-j\beta_2 z)$, where $u_2(y) = \sqrt{2/d}\sin(2\pi y/d)$. The intensity does not vary with z. (c) The complex amplitude in a mixture of modes 1 and 2, $E(y, z) = u_1(y)\exp(-j\beta_1 z) + u_2(y)\exp(-j\beta_2 z)$. Since $\beta_1 \neq \beta_2$, the intensity distribution changes with z.

In general many modes are excited in the guide resulting in complicated field and intensity patterns that evolve in a complex way as the light propagates down the guide

Fundamentals of Photonics - Saleh and Teich

High Order Fiber Modes



Fiber Optics Communication Technology-Mynbaev & Scheiner

a = fibre core radius

The V Parameter

It is convenient to normalize k_T and γ by defining

$$X = k_T a, \qquad Y = \gamma a. \tag{8.1-12}$$

In view of (8.1-11),

$$X^2 + Y^2 = V^2, \tag{8.1-13}$$

where $V = \mathrm{NA} \cdot k_o a$, from which

$$\boxed{V = 2\pi \frac{a}{\lambda_o} \mathrm{NA}.} \tag{8.1-14}$$

V Parameter

The *V* parameter determines the number of propagating modes, *M*.

$$\boxed{M \approx \frac{4}{\pi^2} V^2.} \tag{8.1-18}$$

Number of Modes
($V \gg 1$)

SALAH & TEICH get this completely wrong:
Wrong staircase, wrong parabolic dependence

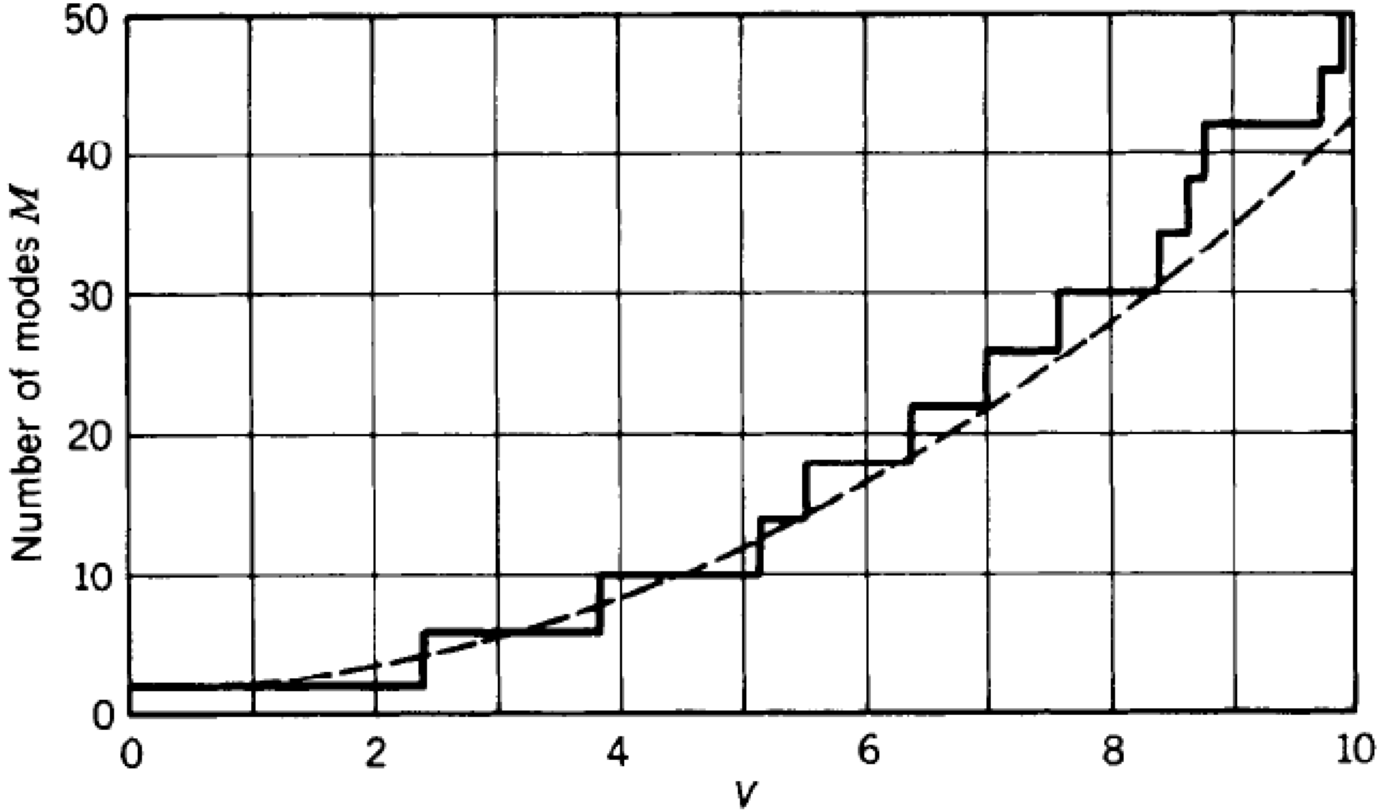
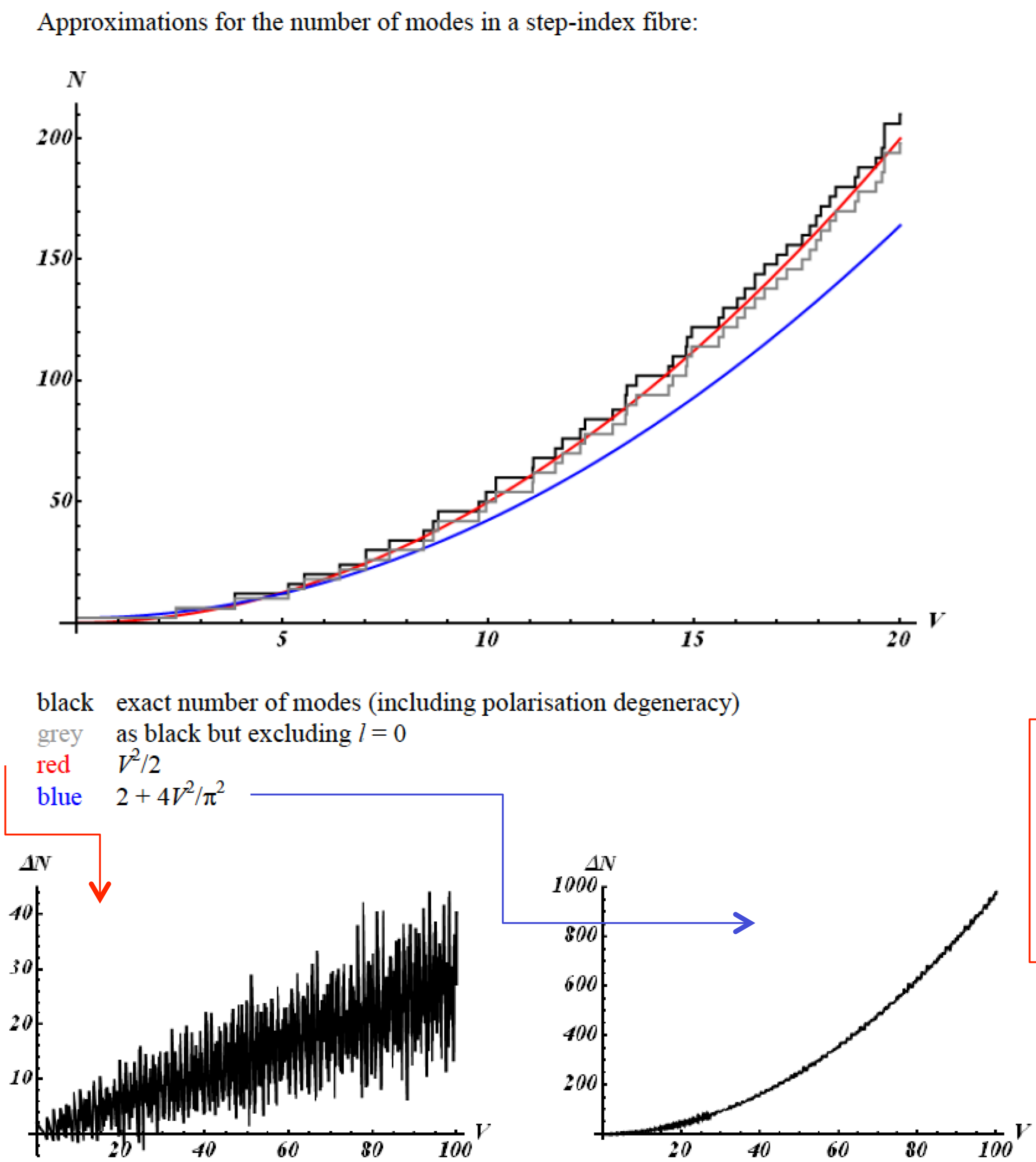


Figure 8.1-8 Total number of modes M versus the fiber parameter $V = 2\pi(a/\lambda_o)\mathrm{NA}$. Included in the count are two helical polarities for each mode with $l > 0$ and two polarizations per mode. For $V < 2.405$, there is only one mode, the fundamental LP_{01} mode with two polarizations. The dashed curve is the relation $M = 4V^2/\pi^2 + 2$, which provides an approximate formula for the number of modes when $V \gg 1$.

We think Saleh & Teich have this wrong (JBH et al 2011, Nature Photonics).



S&T's curve shown in grey: they forgot to include $LP_{0,m}$ where m > 1

And their parabolic function is way off the mark at high V

Correct modes:

***M* = *V* ² / 2**

***M* = *V* ² / 4** (no pol.)

SALAH & TEICH get this completely wrong:

Their worked examples are interesting but *M* should be about 10% higher

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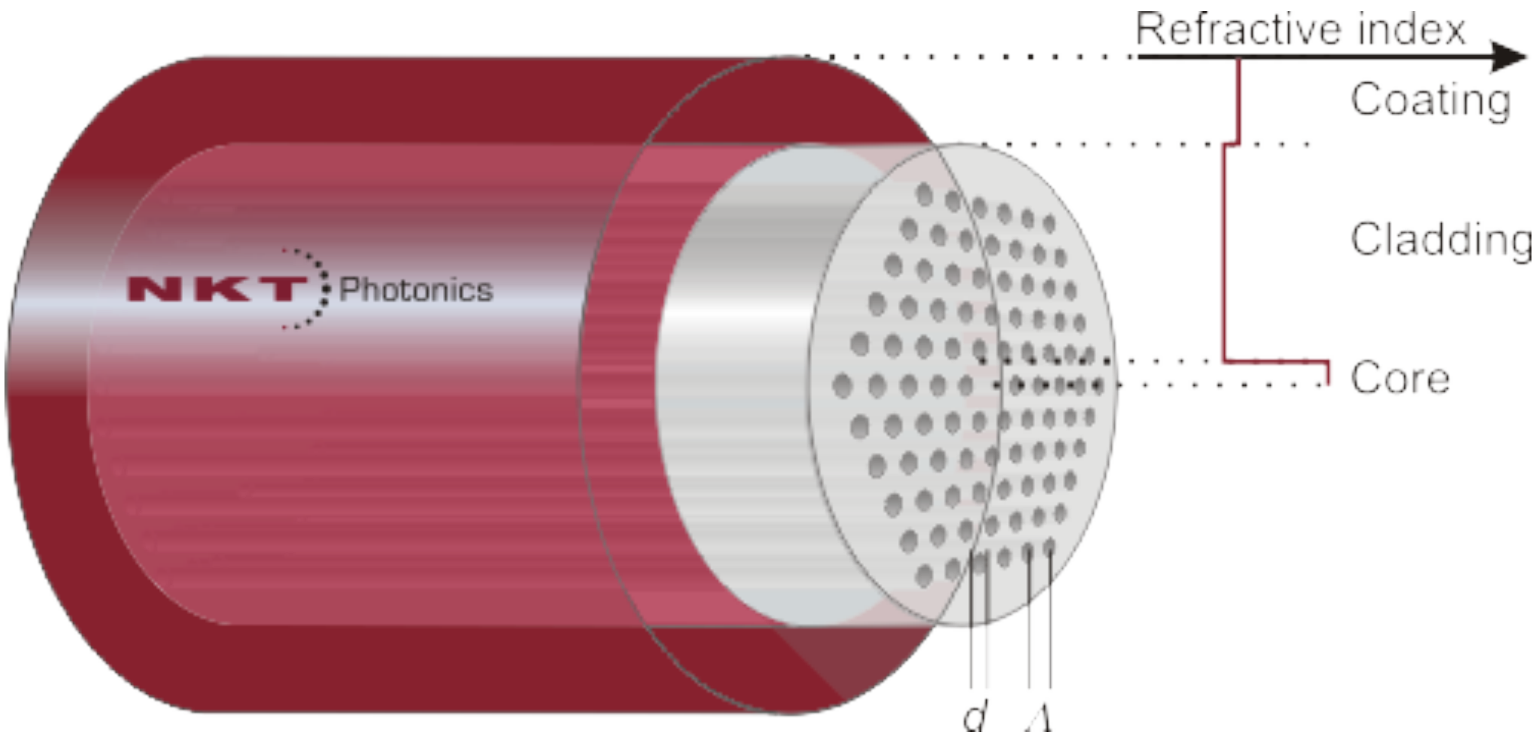
EXAMPLE 8.1-2. ***Approximate Number of Modes.*** A silica fiber with $n_1 = 1.452$ and $\Delta = 0.01$ has a numerical aperture $\mathrm{NA} = (n_1^2 - n_2^2)^{1/2} \approx n_1(2\Delta)^{1/2} \approx 0.205$. If $\lambda_o = 0.85$ μm and the core radius $a = 25$ μm, the V parameter is $V = 2\pi(a/\lambda_o)\mathrm{NA} \approx 37.9$. There are therefore approximately $M \approx 4V^2/\pi^2 \approx 585$ modes. If the cladding is stripped away so that the core is in direct contact with air, $n_2 = 1$ and NA = 1. The V parameter is then $V = 184.8$ and more than 13,800 modes are allowed.

EXAMPLE 8.1-3. ***Single-Mode Operation.*** A silica glass fiber with $n_1 = 1.447$ and $\Delta = 0.01$ (NA = 0.205) operates at $\lambda_o = 1.3$ μm as a single-mode fiber if $V = 2\pi(a/\lambda_o)\mathrm{NA} < 2.405$, i.e., if the core diameter $2a < 4.86$ μm. If Δ is reduced to 0.0025, single-mode operation requires a diameter $2a < 9.72$ μm.

Photonic crystal fibres (PCF)



The guiding properties are determined by the hole sizes, separations and patterns. Invented by our colleague Phillip Russell in 1996. Sometimes there is a large central hole, or a central region devoid of holes, etc. There are very many permutations, active R&D.

Subaru AO system in Hawaii uses these to transport powerful laser light for producing artificial stars – so-called "large mode-area" PCF – i.e. decrease d, increase Λ. Even small changes lead to dramatic LMA performance.

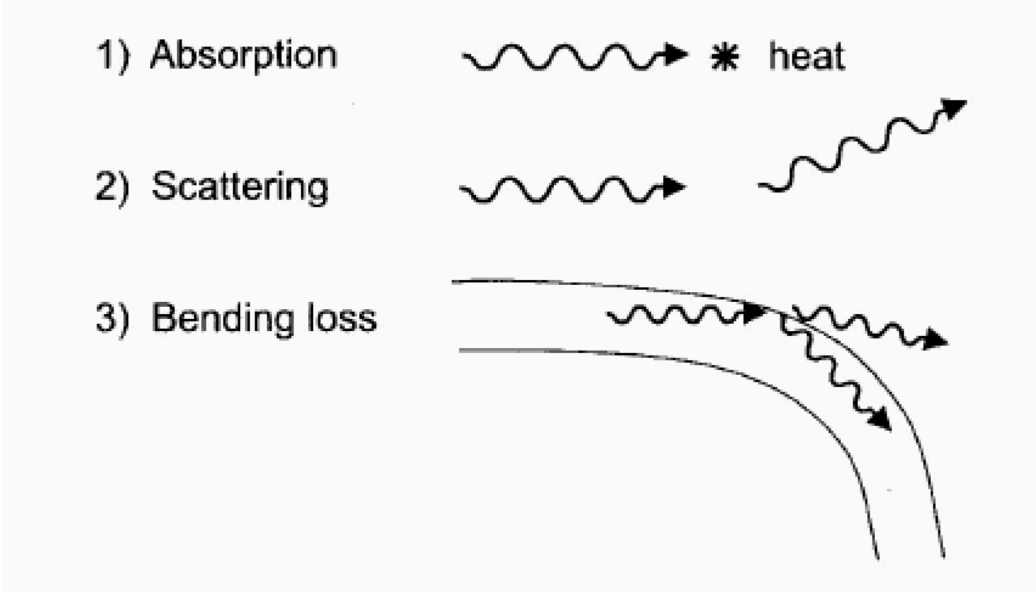
Attenuation/Loss In Optical Fibres

Mechanisms:

Bending loss

Absorption

Scattering loss



Sometimes quoted as dBm which refers to a ratio with respect to a signal of 1 mW

α is usually expressed in dB/km

$$\alpha(dB/km) = -\frac{10}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

$$\text{dB loss} = 10\log_{10}\left(\frac{P_{in}}{P_{out}}\right) = 10\log_{10}(e^{\alpha L}) = 10\,\alpha L\log_{10} e$$

$$\text{dB loss} = 4.34\,\alpha L$$

Note that positive α means loss

Fused silica SiO_2

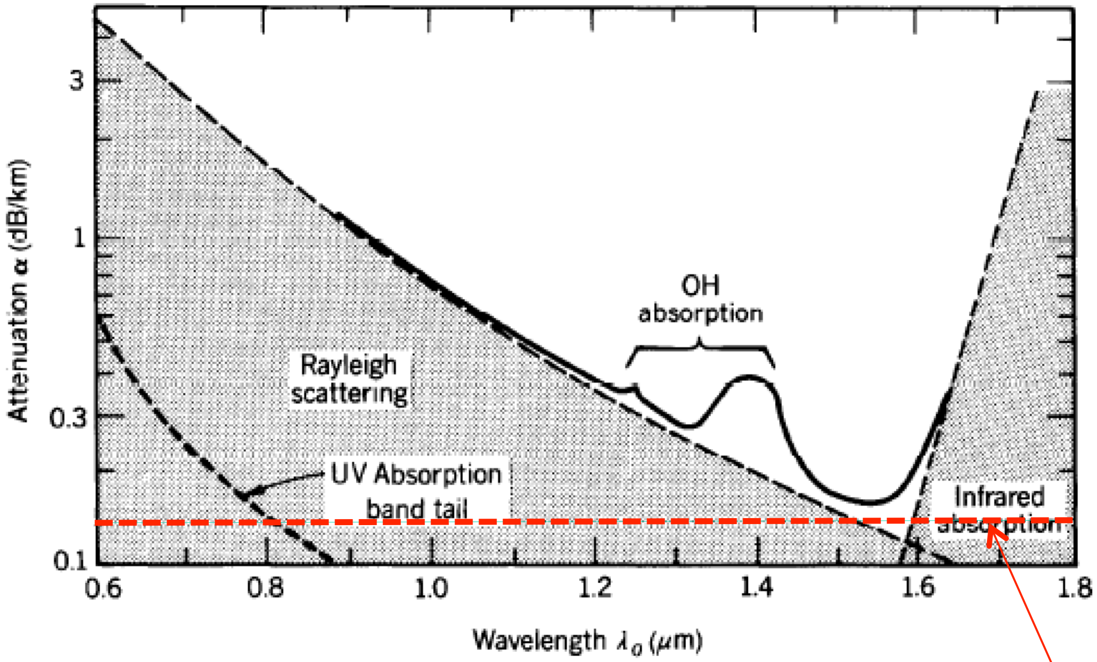


Figure 8.3-2 Dependence of the attenuation coefficient α of silica glass on the wavelength λ_o. There is a local minimum at 1.3 μm ($\alpha \approx 0.3$ dB/km) and an absolute minimum at 1.55 μm ($\alpha \approx 0.16$ dB/km).

P_{out}/P_{in}	dB loss
100.00%	0.00
90.00%	-0.46
80.00%	-0.97
70.00%	-1.55
60.00%	-2.22
50.00%	-3.01
40.00%	-3.98
30.00%	-5.23
20.00%	-6.99
10.00%	-10.00
9.00%	-10.46
8.00%	-10.97
7.00%	-11.55
6.00%	-12.22
5.00%	-13.01
4.00%	-13.98
3.00%	-15.23
2.00%	-16.99
1.00%	-20.00

OH absorption is due to water vapour dissolved in the glass; OH radicals can now be removed. Need to be wary of adding dopants.

Manufacturing Imperfections (this floor has dropped over the years)

Bending Loss

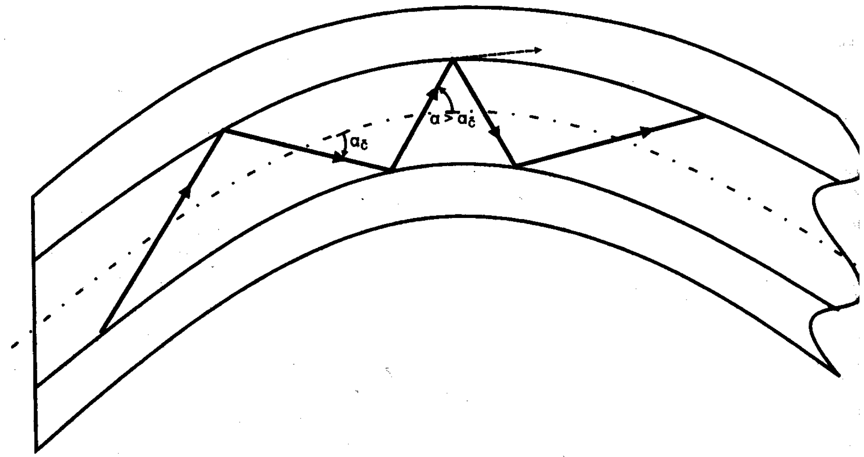
Example bending loss

1 turn at 32 mm diameter
causes 0.5 db loss

Index profile can be adjusted to reduce loss but this degrades the fibre's other characteristics

This loss is ***mode dependent***

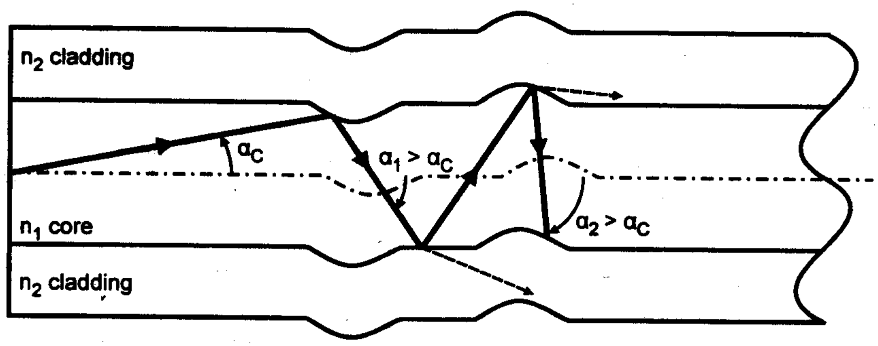
Bend losses can be useful if you want to remove specific modes.



- Outside portion of evanescent field has longer path length, must go faster to keep up
- Beyond a critical value of r, this portion of the field would have to propagate faster than the **speed of light** to stay with the rest of the pulse
- Instead, it radiates out into the cladding and is lost
- Higher-order modes affected more than lower-order modes; bent fiber guides fewer modes

Microbending loss

Property of fiber, under control of fabricator, now very small, usually included in the total attenuation numbers



Fiber Optics Communication Technology-Mynbaev & Scheiner

NOTE: We must also worry about Stresses along fibre, and end faces

Optical fibres:

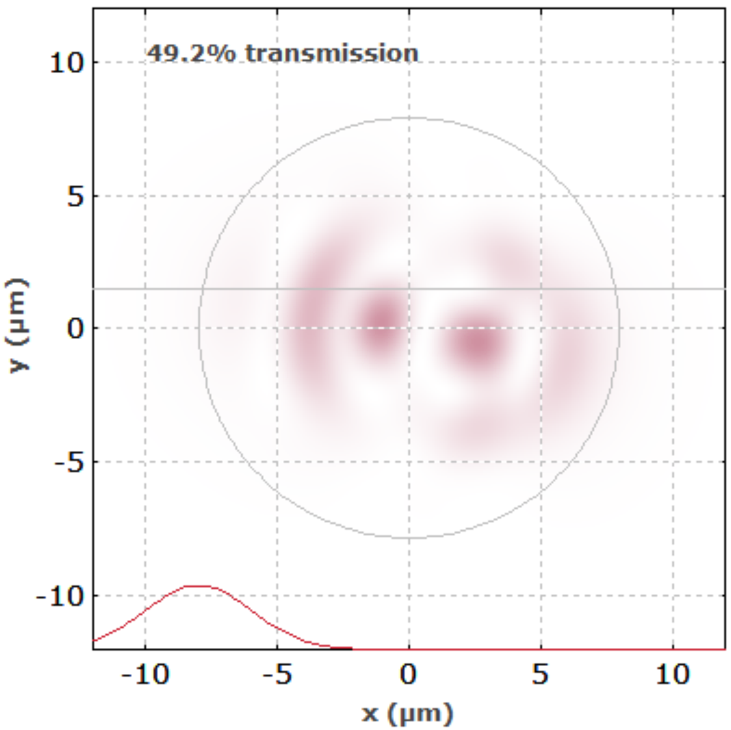
Illumination, coupling

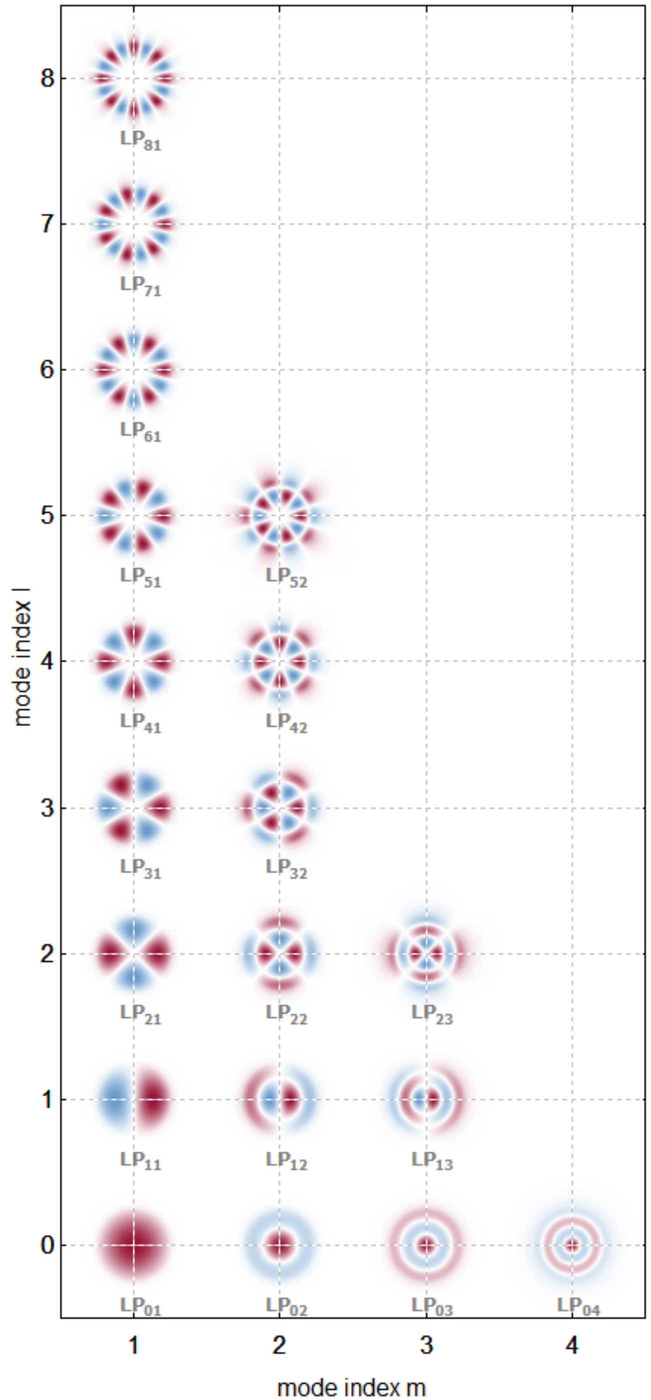
MODES & ILLUMINATION

$$V = 2\pi \frac{a}{\lambda_0} NA$$

As the radius ***a*** increases, the fibre supports an increasing number of spatial modes $LP_{l,m}$ for light propagation.

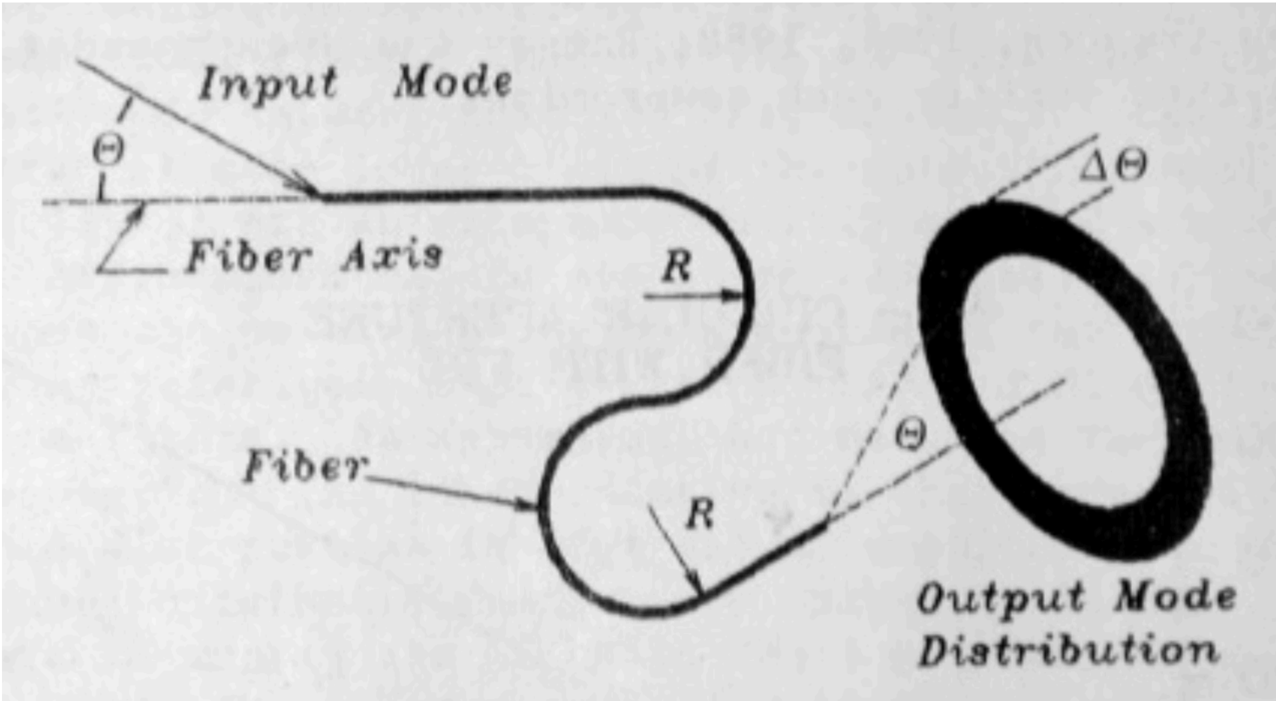
You can see these modes in the lab. With care, you can excite a small family of modes with a laser source depending on the tilt angle, position and illumination pattern.





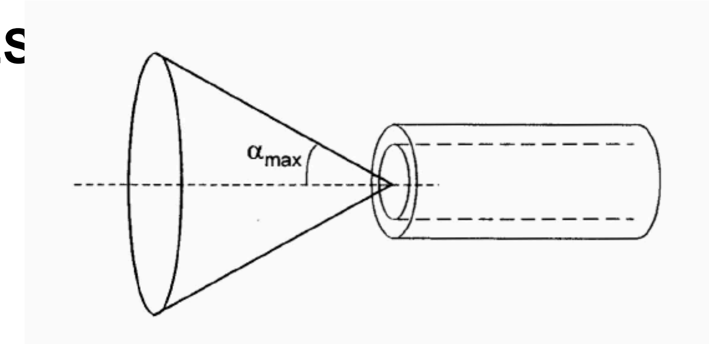
On-axis gaussian beam on input looks the same on output (but with speckle pattern if using laser).

Tilted beam on input generates an annulus on output – the bigger the angle, the larger the radius.



COUPLING LIGHT INTO SINGLE-MODE FIBRES

Getting light into SMFs is notoriously difficult, even for the telecom industry.



Coupling starlight into single-mode fiber optics

Stuart Shaklan and Francois Roddier

We have calculated the efficiency with which starlight can be coupled into a single-mode fiber optic that is placed in the focal plane of a telescope. The calculations are performed for a wide range of seeing conditions, with and without rapid image stabilization, and for a wide range of wavelengths. The dependence of coupling efficiency on the *f*-ratio of the incident beam is explored. Also, we calculate the coupling efficiency as a function of displacement for a perfect Airy pattern. We have also used a computer program which simulates atmospheric wavefronts to determine the variance of instantaneous coupling efficiency as a function of seeing. In perfect conditions, the maximum efficiency at the LP_{11} mode cutoff is 78% due to the mismatch of the Airy pattern and the nearly Gaussian mode of the fiber. Maximum total coupled power is attained at $d/r_0 = 4$ with rapid image stabilization.

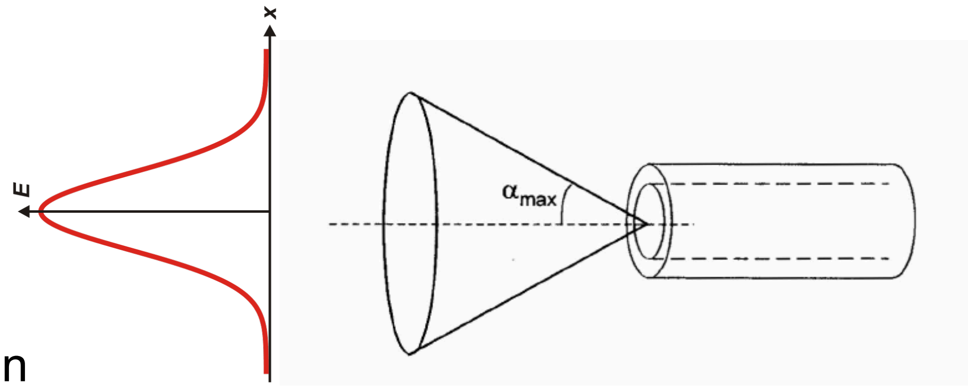
APPLIED OPTICS / Vol. 27, No. 11 / 1 June 1988

Coude du Foresto+ 2000 at Kitt Peak found <5% efficient in natural seeing.

COUPLING LIGHT INTO SINGLE-MODE FIBRES

The Gaussian beam width with radius $\boldsymbol{\rho}$ (e.g. laser) imaged onto the fibre face should match the modal diameter (radius ≈ ***a***)

$$\frac{P_1}{P_0} = \left(\frac{2\rho a}{\rho^2 + a^2} \right)^2$$



Compare this to uniform illumination (e.g. LED); a big effect if $\boldsymbol{\rho = a}$

$$\frac{P_1}{P_0} = \left(\frac{2\rho a}{\rho^2 + a^2} \right)^2 \left\{ 1 - \exp\left(-\frac{1}{2} \frac{\rho^2}{a^2} \right) \right\}^2$$

SMFs require matched Gaussian beams normal to front face, aligned with fibre axis.

Snyder and Love (1983) book give formulae for beam tilted w.r.t. front face, and offset w.r.t. front face (see Table 20-1).

Coupling light into few-mode optical fibres I: The diffraction limit

Anthony J. Horton and Joss Bland-Hawthorn

Anglo-Australian Observatory, PO Box 296, Epping, NSW, Australia

ajh@aao.gov.au

Abstract: Multimode fibres are widely used in astronomy because of the ease of coupling light into them at a telescope focus. The photonics industry has given rise to a broad range of products but these are almost exclusively restricted to single-mode fibres, although some can be adapted for use in fibres that allow several modes to propagate. Now that astronomical telescopes are moving toward diffraction-limited performance through the use of adaptive optics (AO), we address the problem of coupling light into a few-mode fibre (FMF). We find that fibres with as few as $\sim$5 guided modes share important characterisitcs with multimode fibres, in particular high coupling efficiency. We anticipate that future astronomical instruments at an AO-corrected focus will be able to exploit a broad class of photonic devices.

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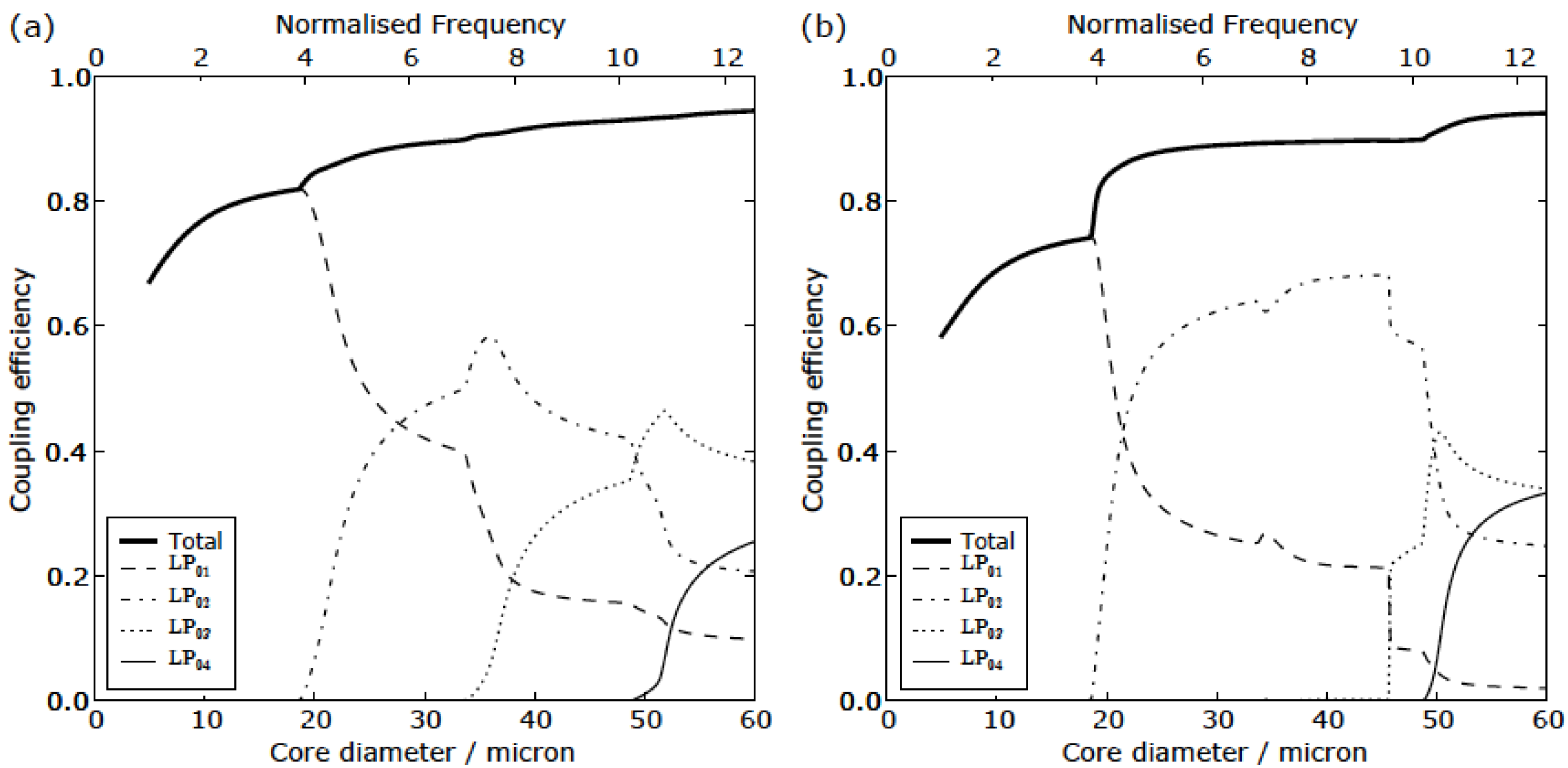
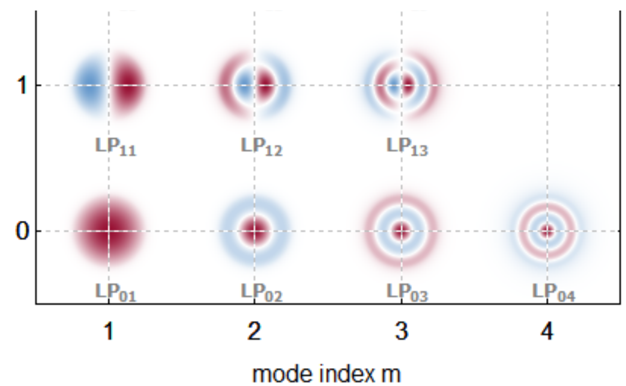
OCIS codes: (060.2310) Fibers optics; (010.1080) Adaptive optics; (060.2430) Fibers, single-mode; (999.9999) Fibers, few-mode



Telescope mirrors have a hole in the centre:

(LHS) no hole; (RHS) 15% hole.



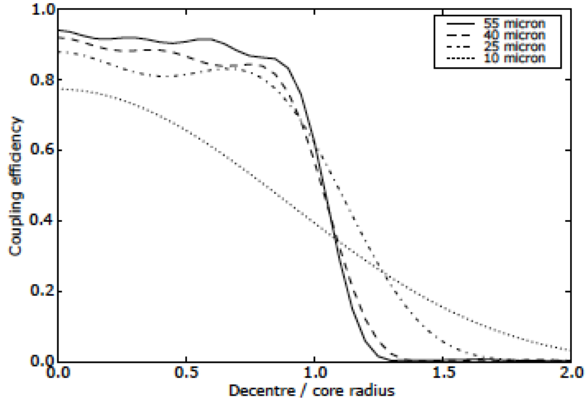


Fig. 4. Coupling efficiency versus decentring of the image centre from the fibre axis. Coupling efficiency is shown for NA = 0.1 fibres with 10, 25, 40 and 55μm core diameters at a wavelength of 1.5μm and with $\alpha = 0$.

Quite resilient to physical offsets

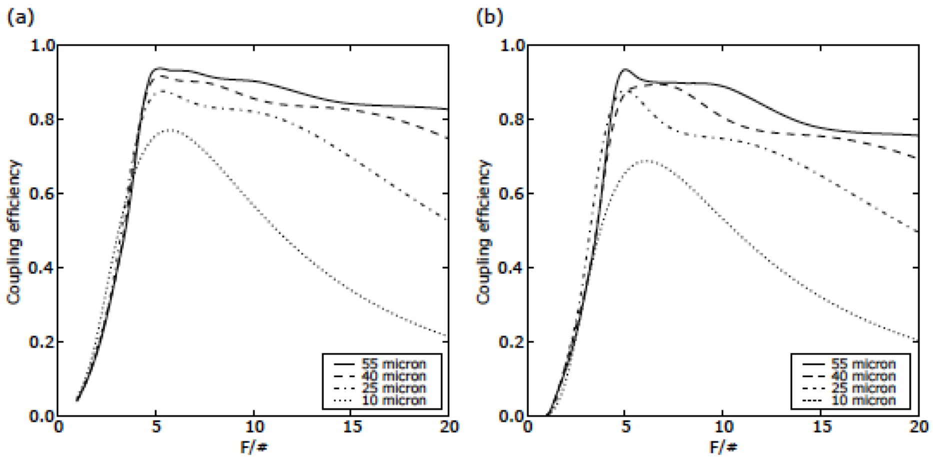
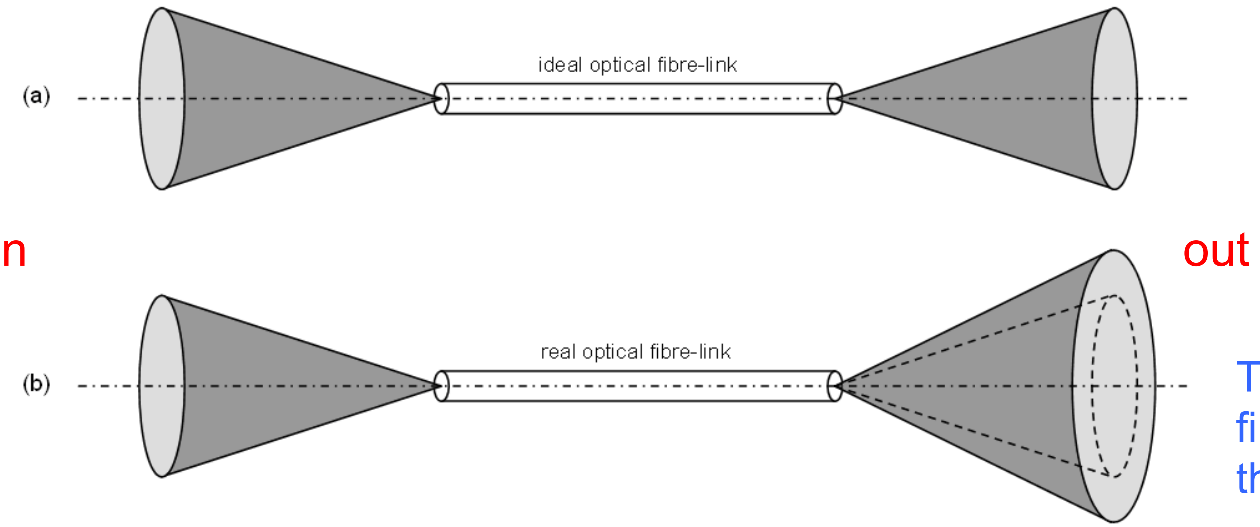


Fig. 3. Coupling efficiency versus focal ratio for an NA = 0.1 fibre at a wavelength of 1.5μm. Coupling efficiency is shown for core diameters of 10, 25, 40 and 55μm with (a) $\alpha = 0$ and (b) $\alpha = 0.2$.

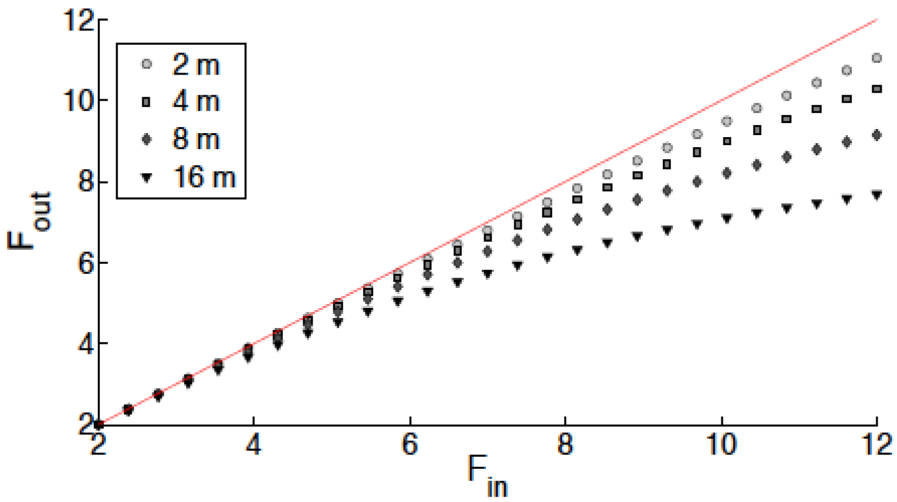
Prefer slower beams

FOCAL RATIO DEGRADATION (FRD), a.k.a. NA upscattering

For an input beam with smaller NA than fibre



This assumes the fibre NA supports the output beam



Analytically derived from formulae by Gloge (1971) and Snyder & Love (1983) where light in any give mode (angle to fibre axis) gets scattered. Since higher modes have more volume, light tends to scatter from low to high modes, until natural NA of fibre is filled.

MATCHING OPTICS TO FIBRES

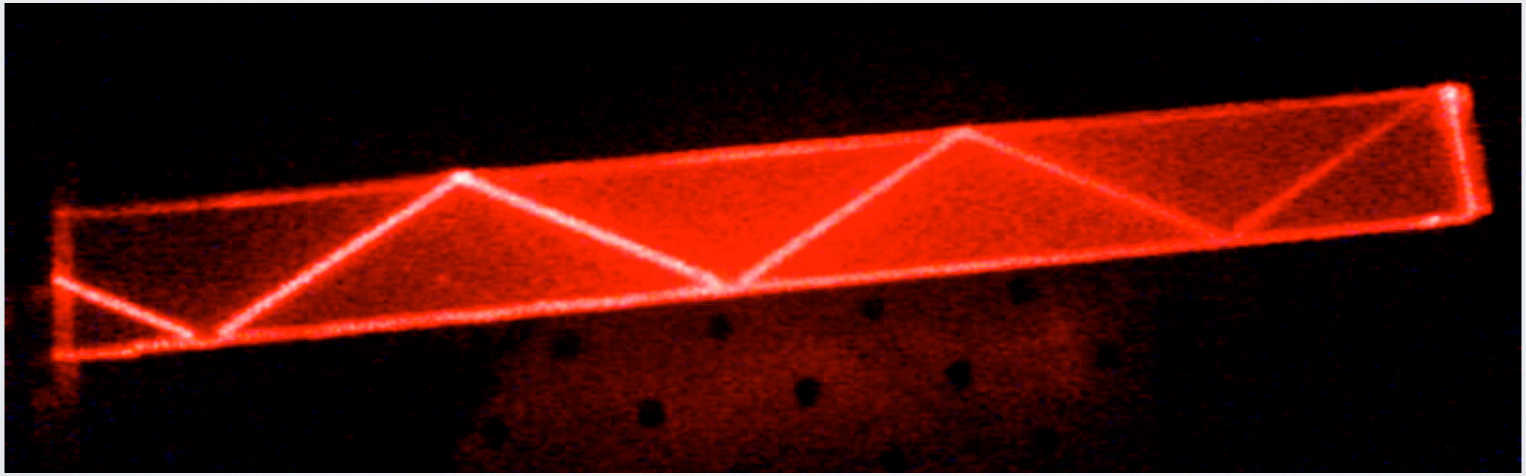
A common rule of thumb is that an optic with f/ratio = f/*N* should be matched to a fibre with an *NA* = *1/2N, e.g. N=5* matched to *NA=0.1.*

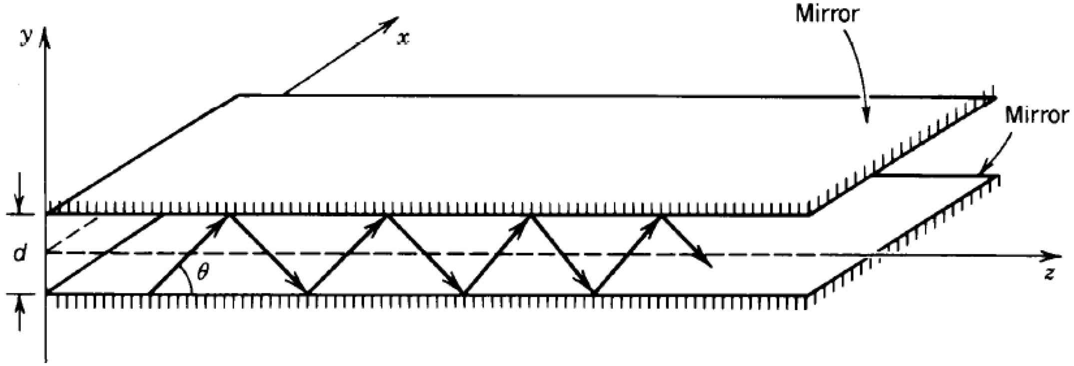
But this has two problems: (i) FRD considerations; (ii) matching FWHM means that you will miss light. Both conditions mean that you normally need to use faster, i.e. wider angle beams, than simple matching dictates.

FRD is a real problem because it forces you to fast output optics which are very expensive and harder to ensure broadband performance. Nobody has truly demonstrated fibres that are free of FRD, even those with highest purity. Keeping fibre lengths shorter than a few metres can help.

2D waveguides:

Guiding, losses, properties





Infinite reflecting mirrors

Geometric condition:

$$\sin\theta_m = m\frac{\lambda}{2d}, \qquad m = 1, 2, \ldots .$$

Transverse wavenumber:

$$k_{ym} = m\frac{\pi}{d}, \qquad m = 1, 2, 3, \ldots,$$

Number of transverse modes:

$$M \doteq \frac{2d}{\lambda}.$$

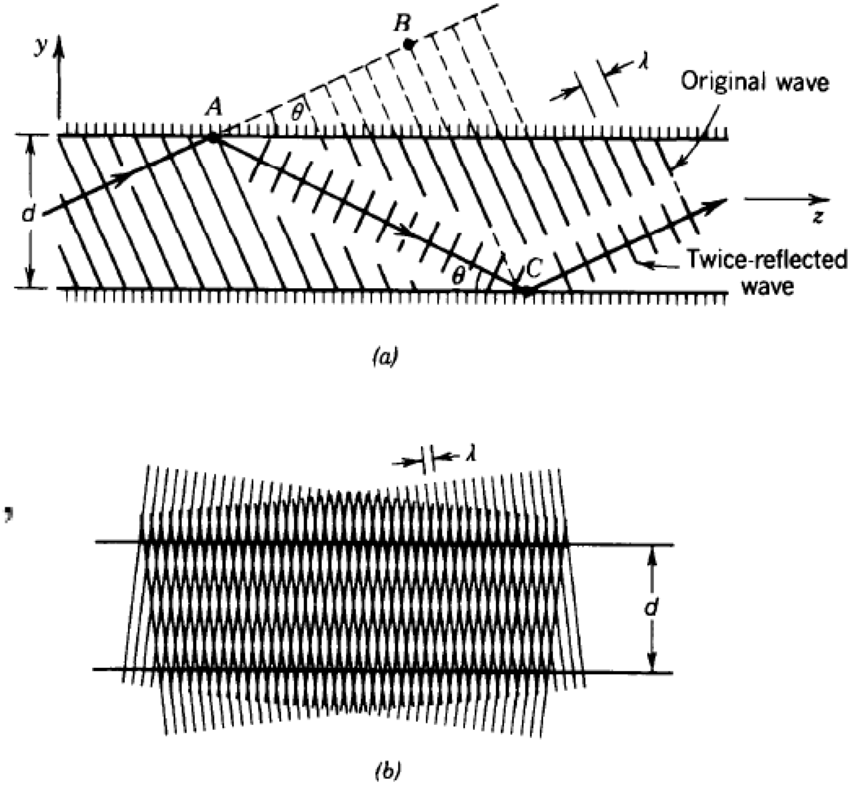
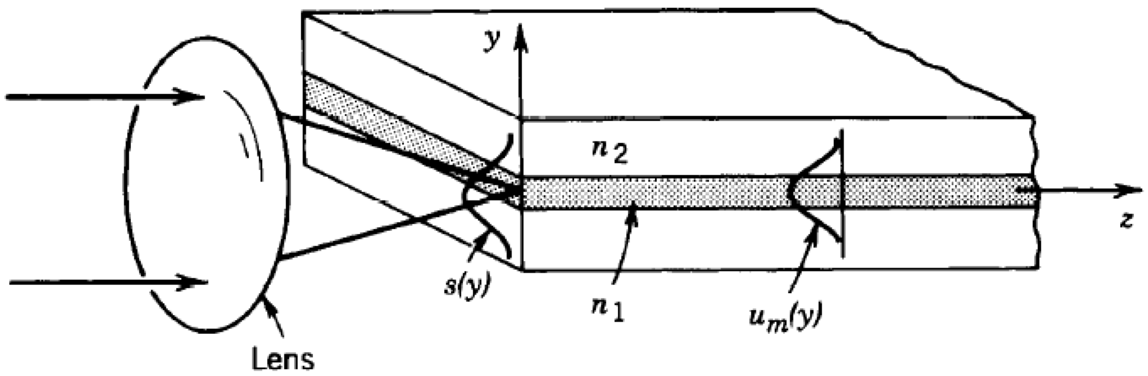


Figure 7.1-2 (*a*) Condition of self-consistency: as a wave reflects twice it duplicates itself. (*b*) At angles for which self-consistency is satisfied, the two waves interfere and create a pattern that does not change with z.

A real waveguide



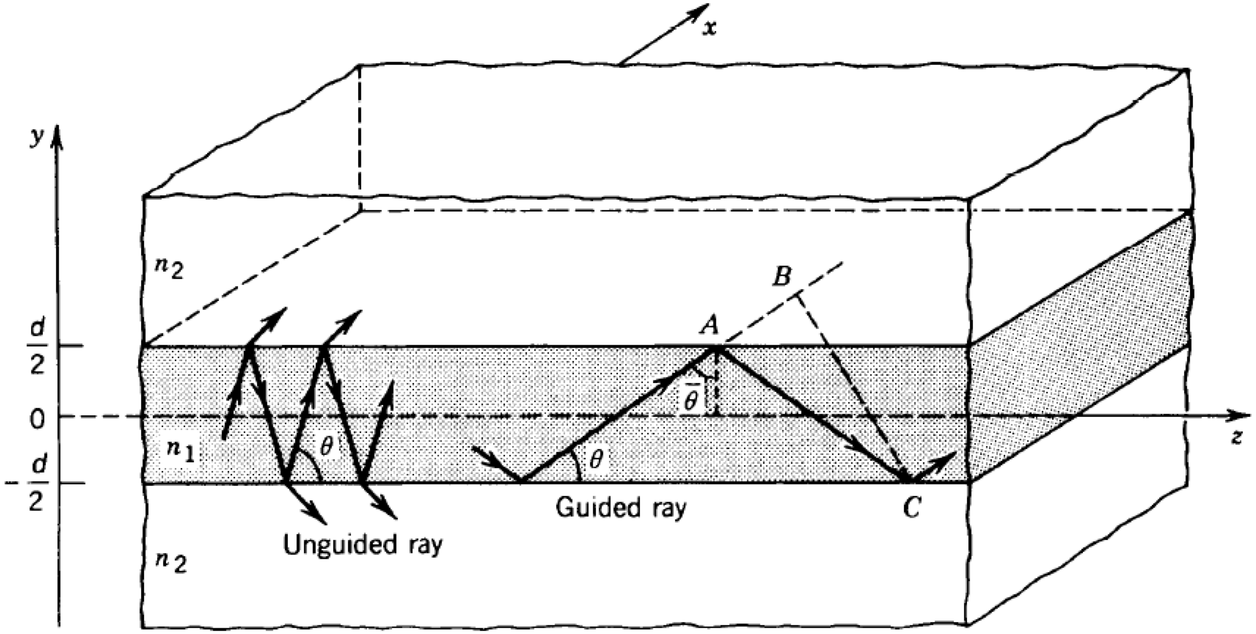


Figure 7.2-1 Planar dielectric waveguide. Rays making an angle $\theta < \bar{\theta}_c = \cos^{-1}(n_2/n_1)$ are guided by total internal reflection.

$$\boxed{M \doteq 2\frac{d}{\lambda_o}\mathrm{NA},}$$

(7.2-7)
Number of TE Modes

$$\boxed{\mathrm{NA} = \left(n_1^2 - n_2^2\right)^{1/2}}$$

(7.2-8)
Numerical Aperture

$$\boxed{\beta_m^2 = k^2 - \frac{m^2\pi^2}{d^2}.}$$

(7.1-4)
Propagation Constants

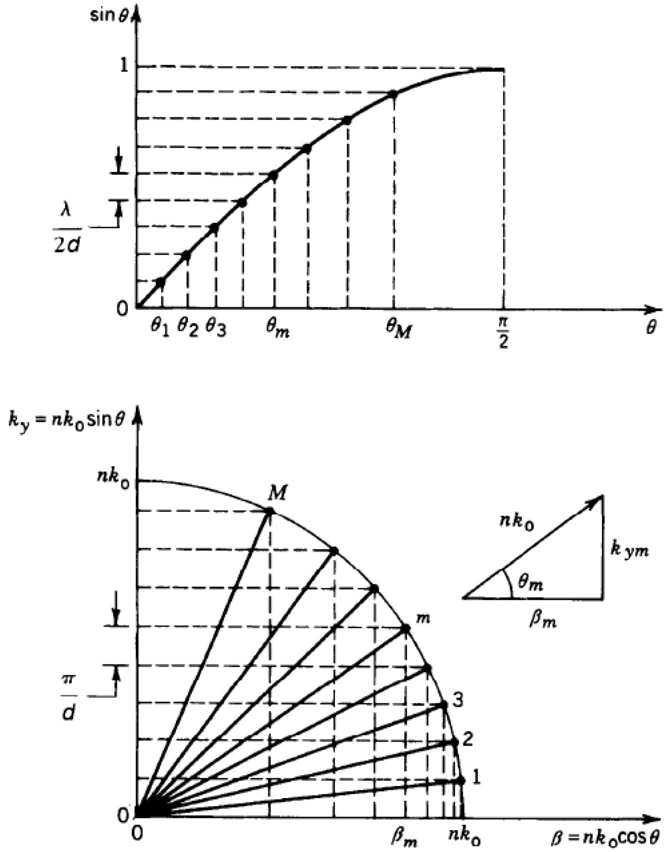


Figure 7.1-3 The bounce angles θ_m and the wavevector components of the modes of a planar-mirror waveguide (indicated by dots). The transverse components $k_{ym} = k \sin\theta_m$ are spaced uniformly at multiples of π/d, but the bounce angles θ_m and the propagation constants β_m are not equally spaced. Mode $m = 1$ has the smallest bounce angle and the largest propagation constant.

DIELECTRIC
WAVEGUIDE

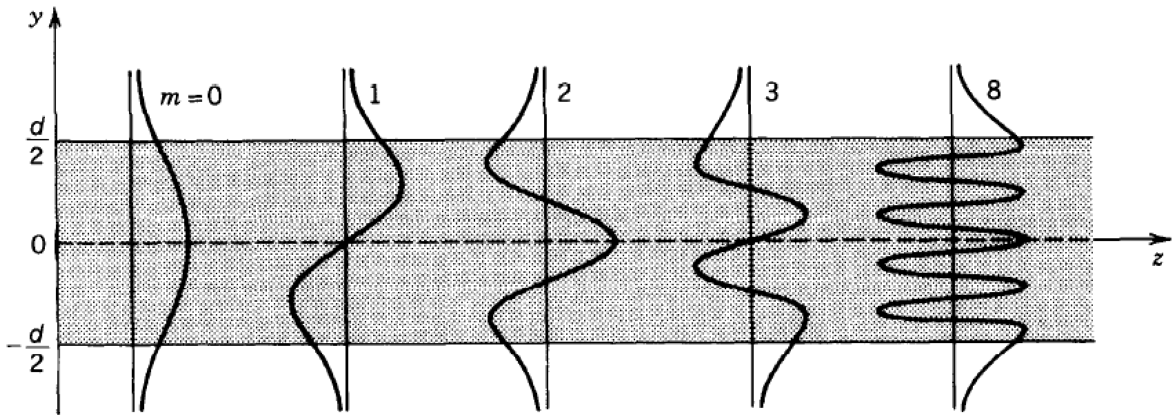
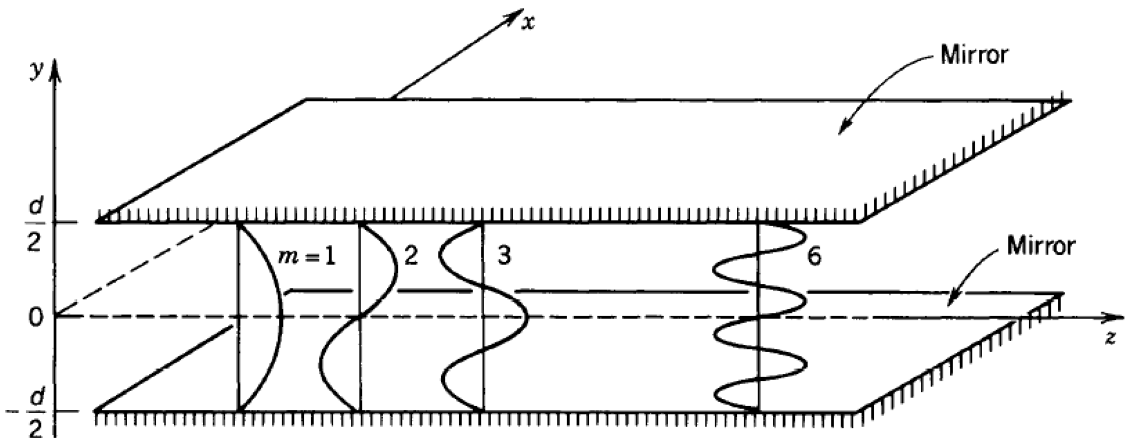


Figure 7.2-5 Field distributions for TE guided modes in a dielectric waveguide. These results should be compared with those shown in Fig. 7.1-4 for the planar-mirror waveguide.

MIRROR
WAVEGUIDE



Many ways to achieve 2D waveguide propagation

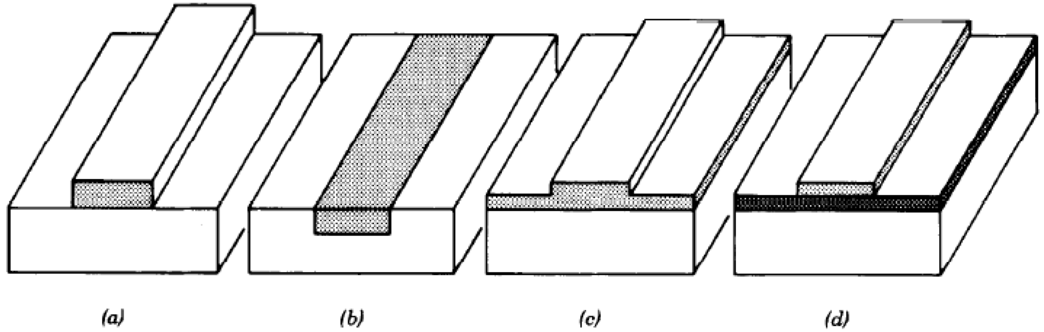
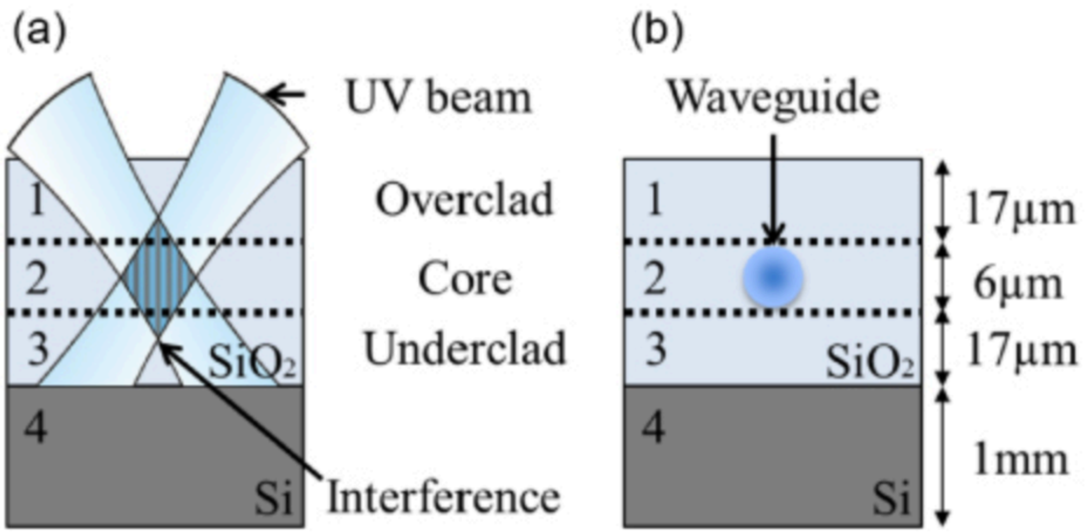


Figure 7.3-3 Various types of waveguide geometries: (*a*) strip; (*b*) embedded strip; (*c*) rib or ridge; (*d*) strip loaded. The darker the shading, the higher the refractive index.

Most common manufacture: Silicon-on-insulator (SOI) = Silica-on-silicon



SiO_2 is an insulator, typically a sub-micron thick layer of oxide grown with an O-rich plasma. On top of that, we may deposit a few micron layer of Si. This entire wafer, typically 4” in size, can be bought for $1000 each. The Si substrate is a solid crystal maybe 500 microns thick. So why is it not insulator on Si ?

Fantastic variety of ways to manipulate light, to mix light between tracks on a waveguide, etc.

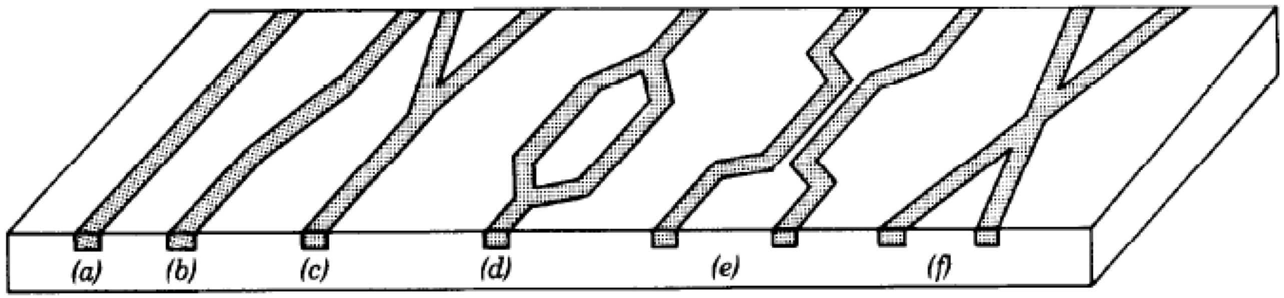
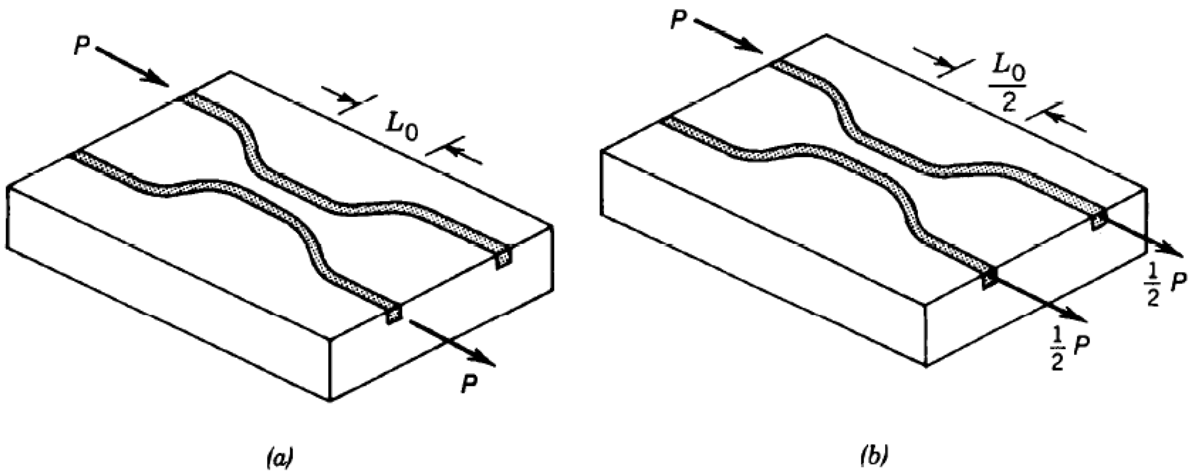
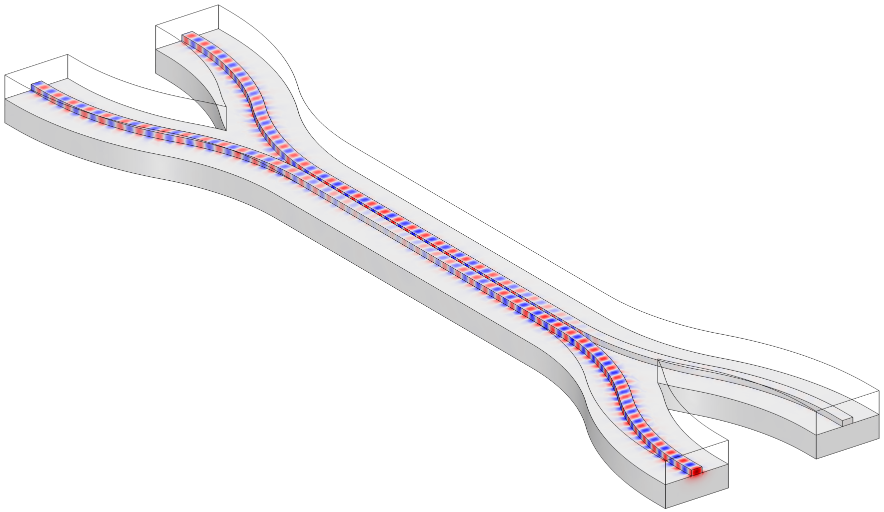


Figure 7.3-4 Different configurations for waveguides: (a) straight; (b) S bend; (c) Y branch; (d) Mach–Zehnder; (e) directional coupler; (f) intersection.

You can split light in half, switch all light to a different track…





$$E_1(y, z) = a_1 u_1(y) \exp(-j\beta_1 z)$$

$$E_2(y, z) = a_2 u_2(y) \exp(-j\beta_2' z)$$

$$\boxed{\begin{aligned} \frac{da_1}{dz} &= -j\mathcal{C}_{21} \exp(j\,\Delta\beta\, z)\, a_2(z) \\ \frac{da_2}{dz} &= -j\mathcal{C}_{12} \exp(-j\,\Delta\beta\, z)\, a_1(z), \end{aligned}}$$

Phase mismatch per unit length

$$\Delta\beta = \beta_1 - \beta_2$$

General solution derived in Saleh & Teich

$$a_1(z) = a_1(0)\exp\left(+\frac{j\,\Delta\beta\, z}{2}\right)\left(\cos\gamma z - j\frac{\Delta\beta}{2\gamma}\sin\gamma z\right)$$

$$a_2(z) = a_1(0)\frac{\mathcal{C}_{12}}{j\gamma}\exp\left(-j\frac{\Delta\beta\, z}{2}\right)\sin\gamma z,$$

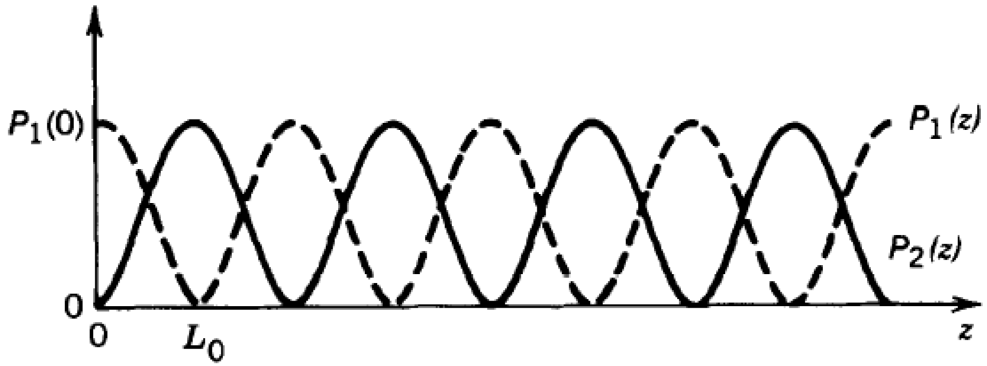
constants

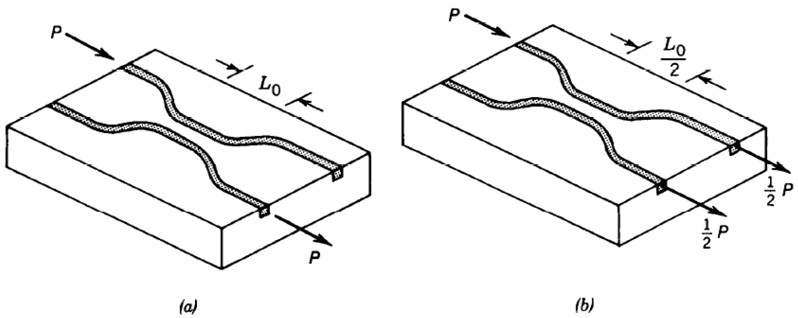
$$\gamma^2 = \left(\frac{\Delta\beta}{2}\right)^2 + \mathcal{C}^2$$

$$\mathcal{C} = (\mathcal{C}_{12}\mathcal{C}_{21})^{1/2}$$

Identical waveguides, $\Delta\beta=0, \gamma=C$, equations simplify to sine waves

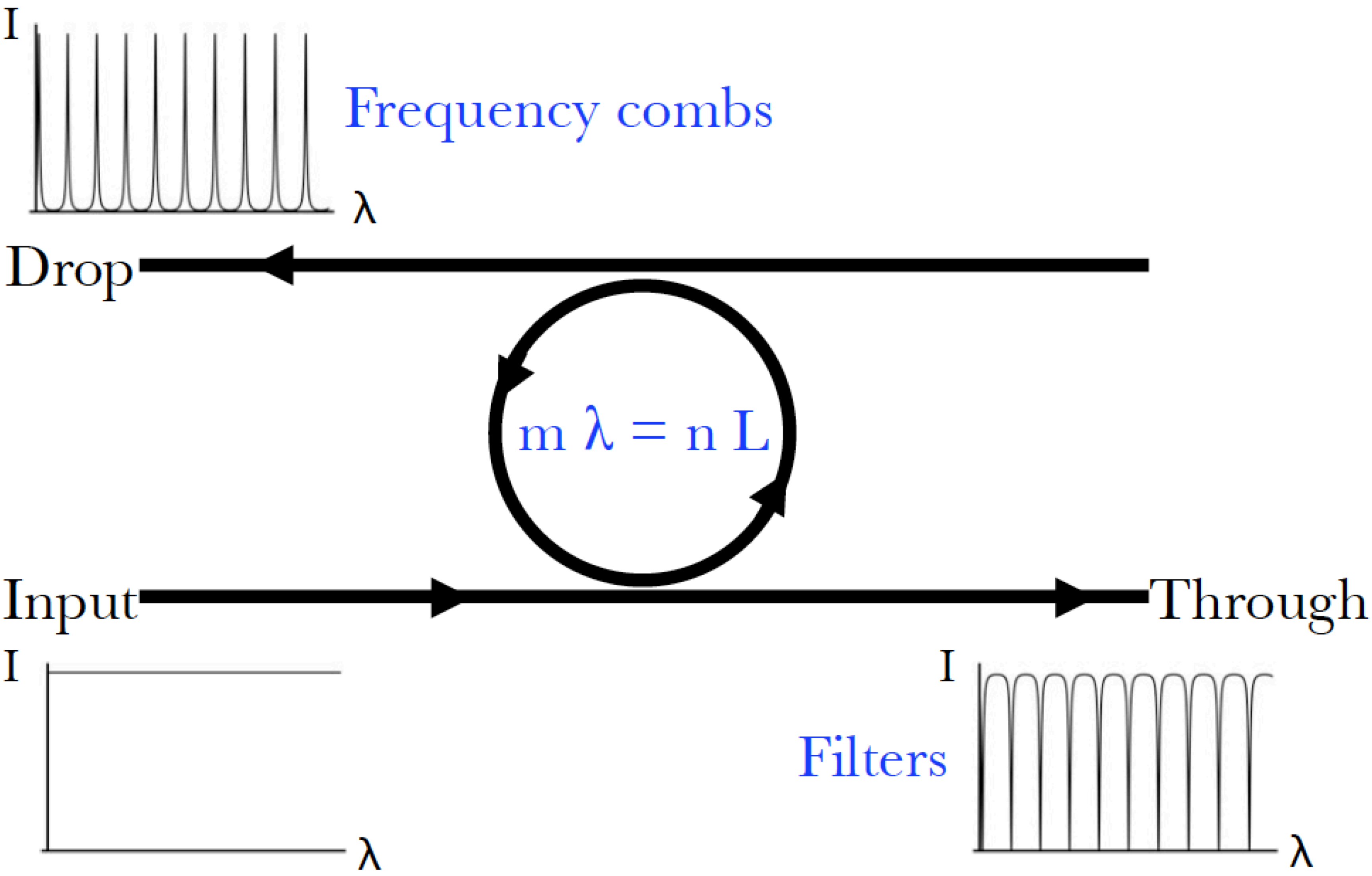
Power swapping between tracks determined by length $L_0=\pi/2C$



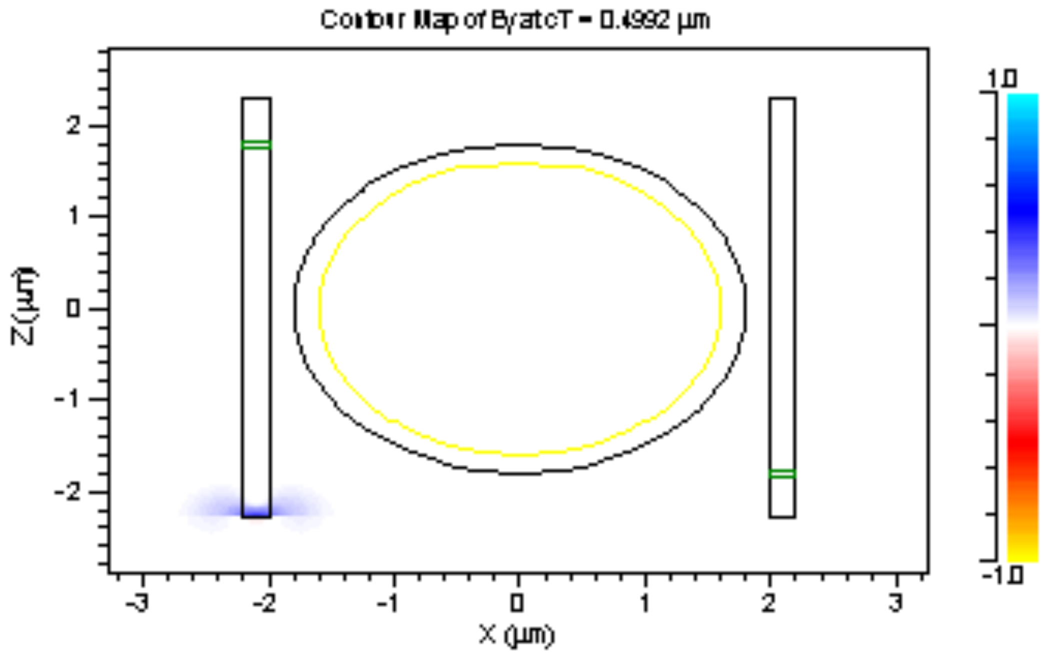


-7 Exchange of power between guides 1 and 2 in the phase-matched case.

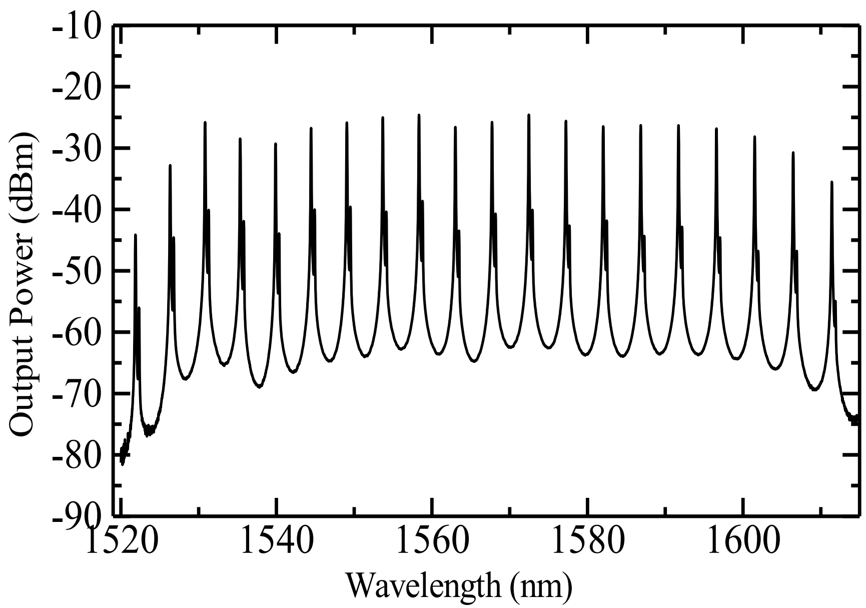
Ring Resonators

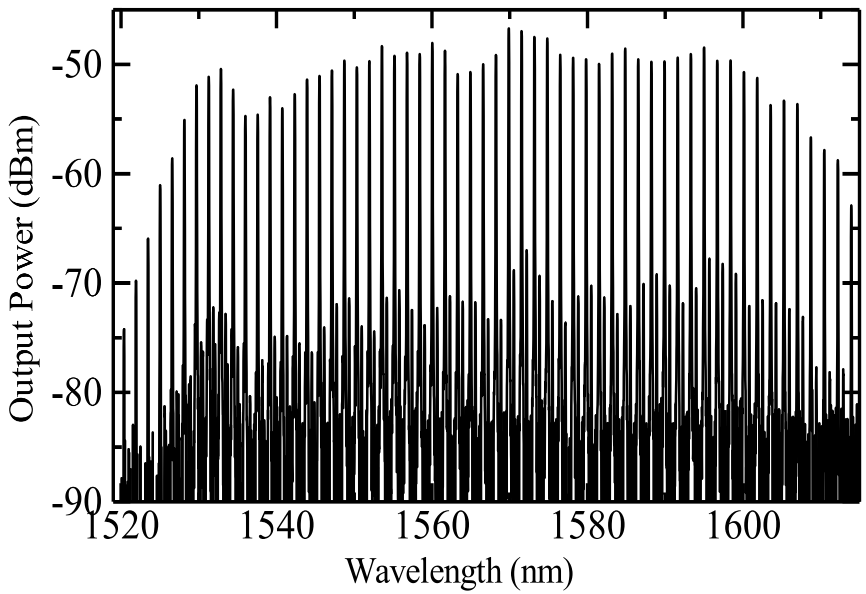


Ring resonator simulation – S.C. Ellis (AAO)

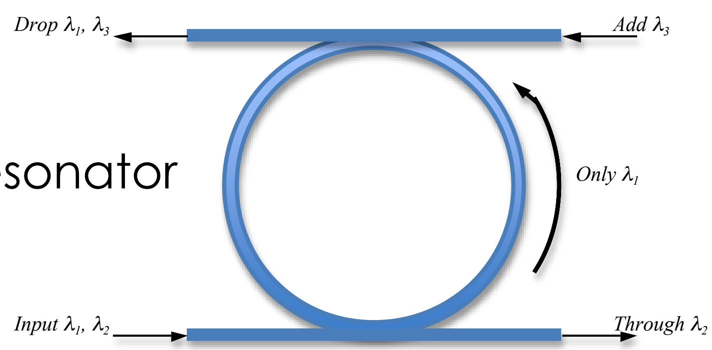


Generate comb for precise calibration





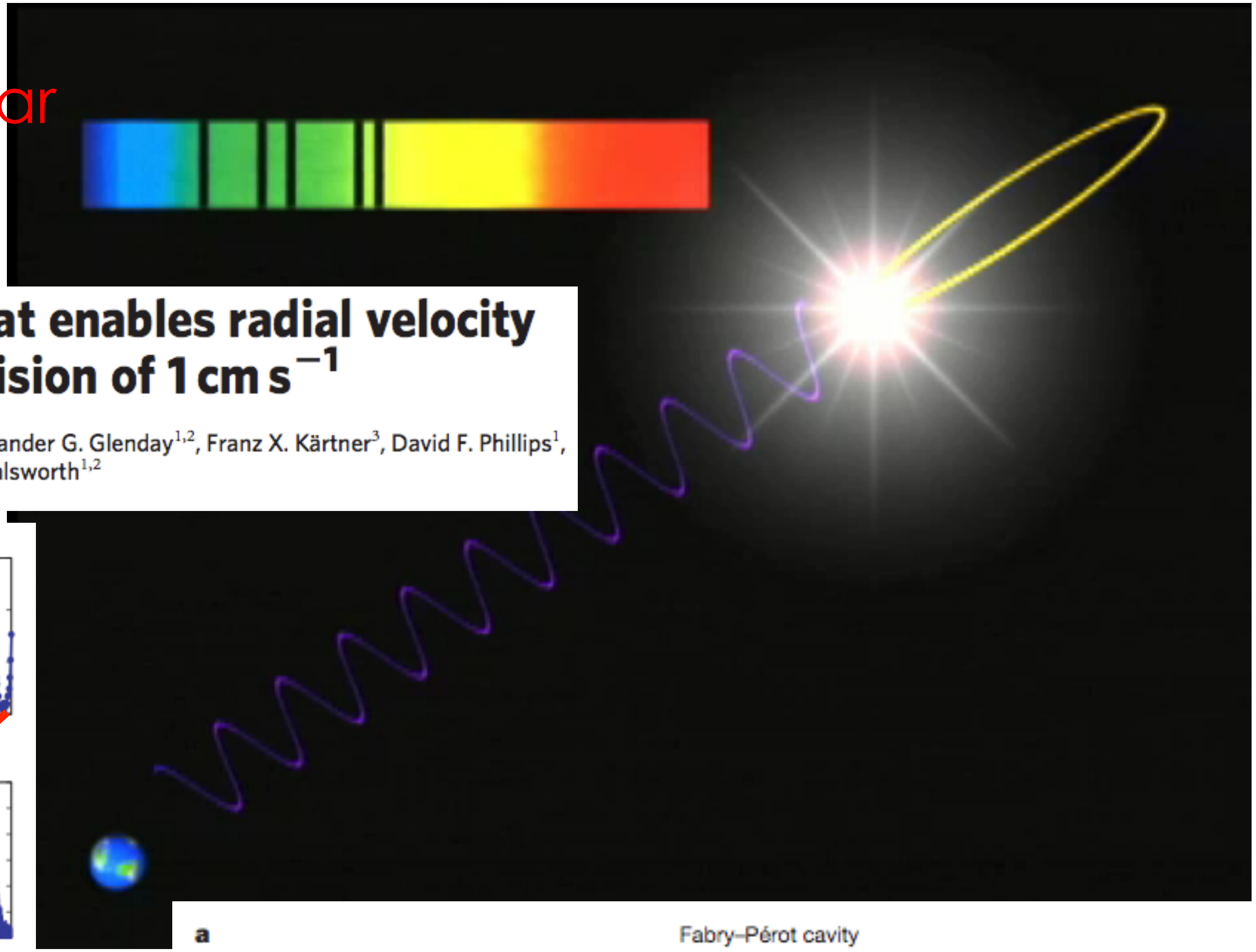
ring resonator



We published this method a few years ago (Chu et al 2012)

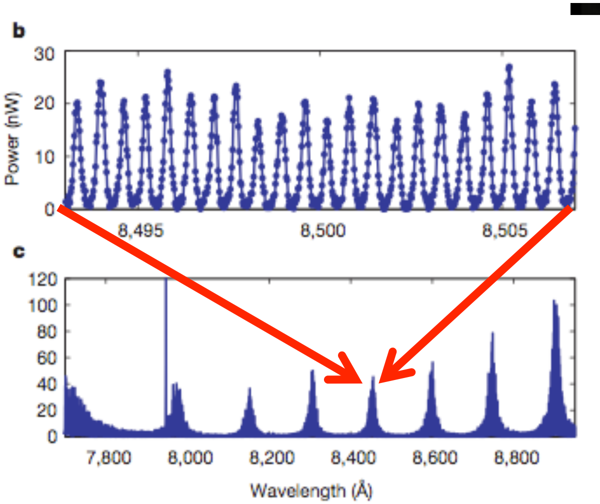
A better approach is to lock a fibre etalon to a Rb laser diode

Hunting for extrasolar planets

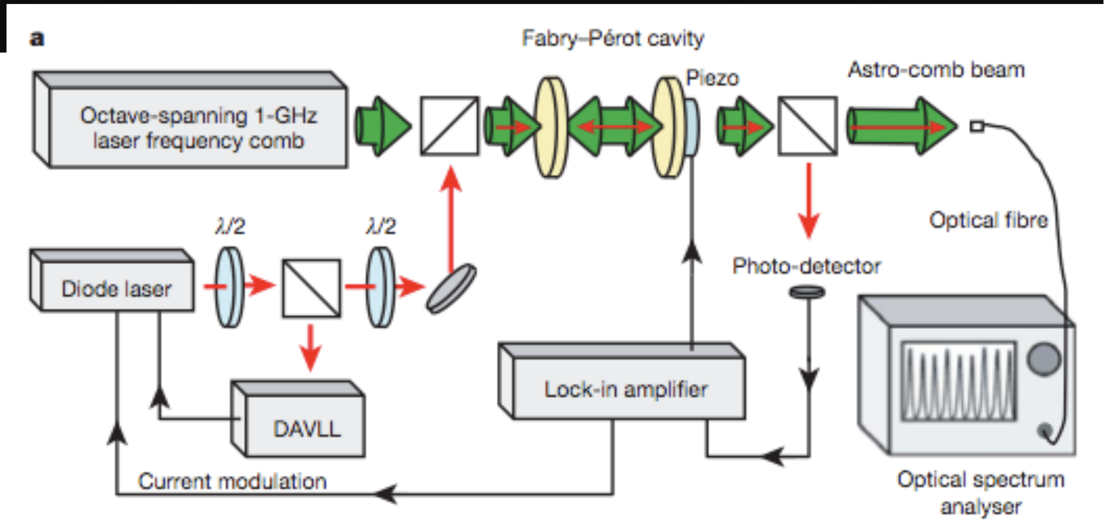


A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}

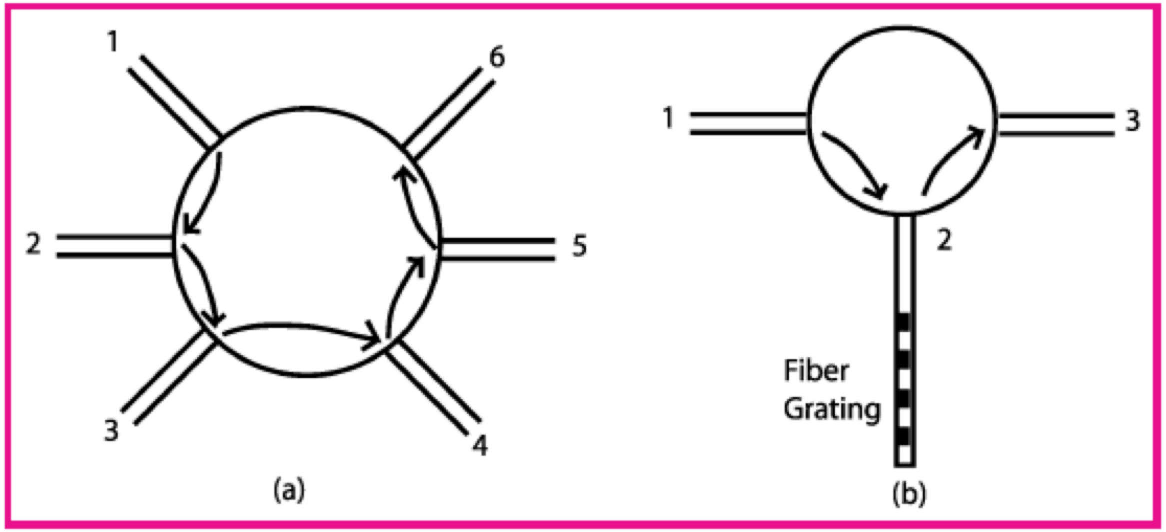
Chih-Hao Li[1,2], Andrew J. Benedick[3], Peter Fendel[3,4], Alexander G. Glenday[1,2], Franz X. Kärtner[3], David F. Phillips[1], Dimitar Sasselov[1], Andrew Szentgyorgyi[1] & Ronald L. Walsworth[1,2]



But spatial stability must also be addressed!

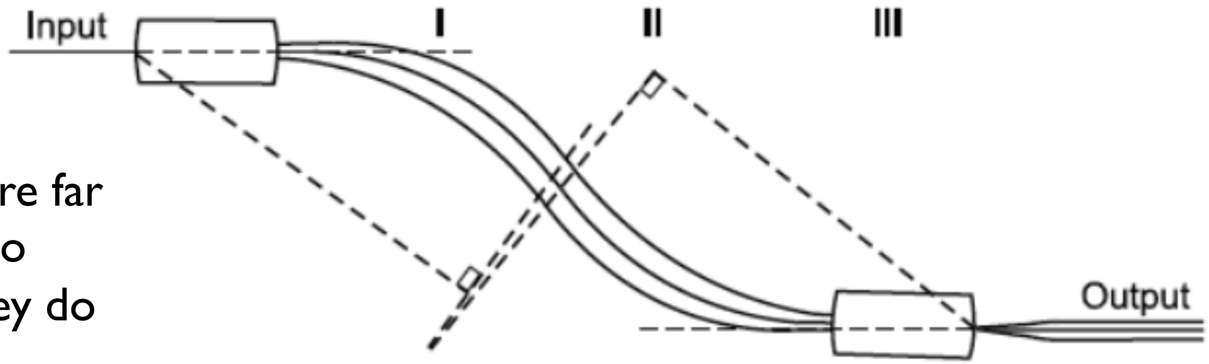


Optical Circulators

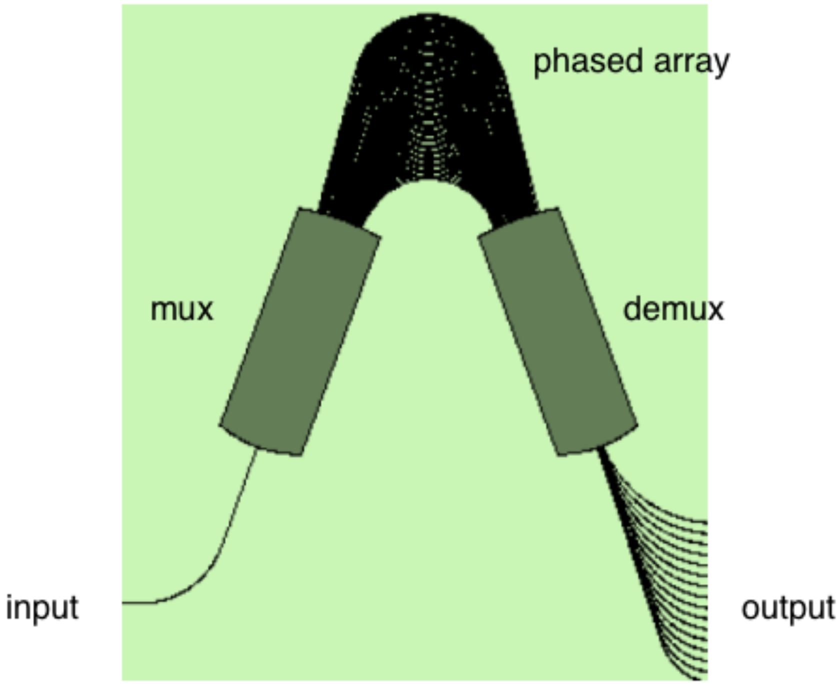


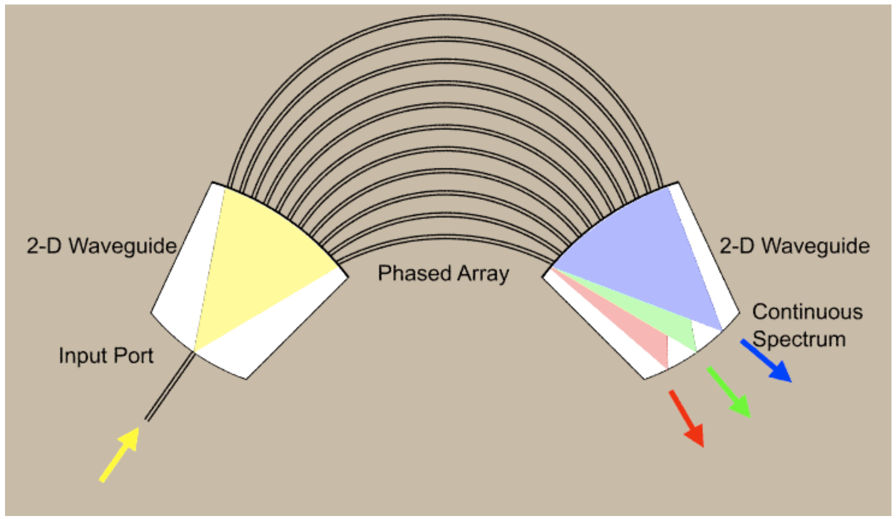
- A circulator directs backward propagating light does to another port rather than discarding it, resulting in a three-port device.
- More ports can be added if necessary.
- Such devices are called circulators because they direct light to different ports in a circular fashion.
- Design of optical circulators becomes increasingly complex as the number of ports increases.

Array Waveguide Grating



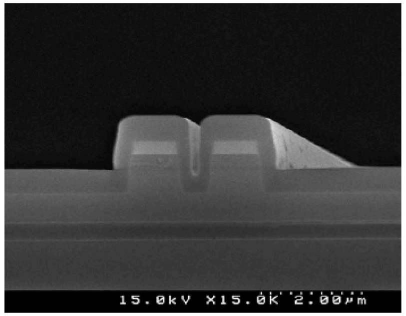
These tracks are far enough apart to ensure that they do NOT couple



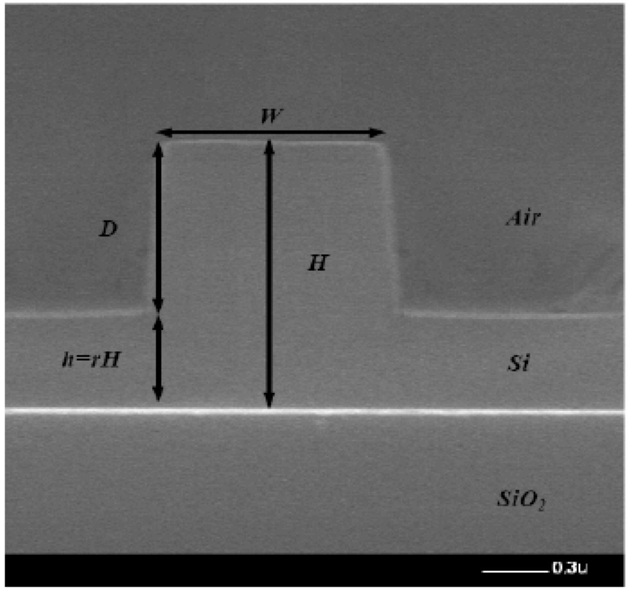


2D WAVEGUIDE LOSSES (SOI)

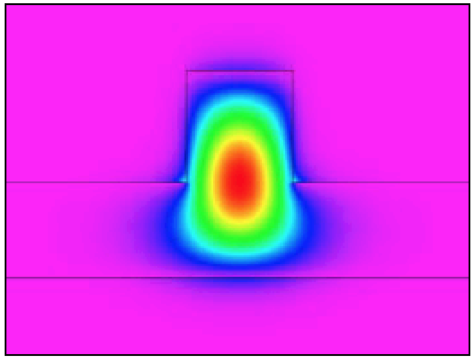
These are typically 0.1 dB/cm for the best rib waveguides but there are additional coupling losses at front face (~0.1 dB).



SEM of a directional coupler made of two rib waveguides with oxide cover

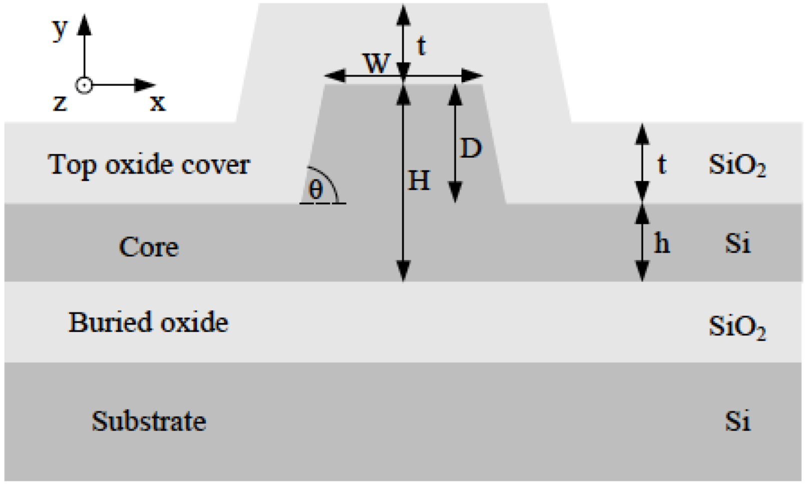


SOI rib waveguide



$$\frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1-r^2}} \qquad (\text{for } 0.5 \leq r < 1)$$

Soref's formula for single mode condition for large rib waveguides



Rib waveguide (H=400 nm to several microns; 0.1 dB/cm loss)

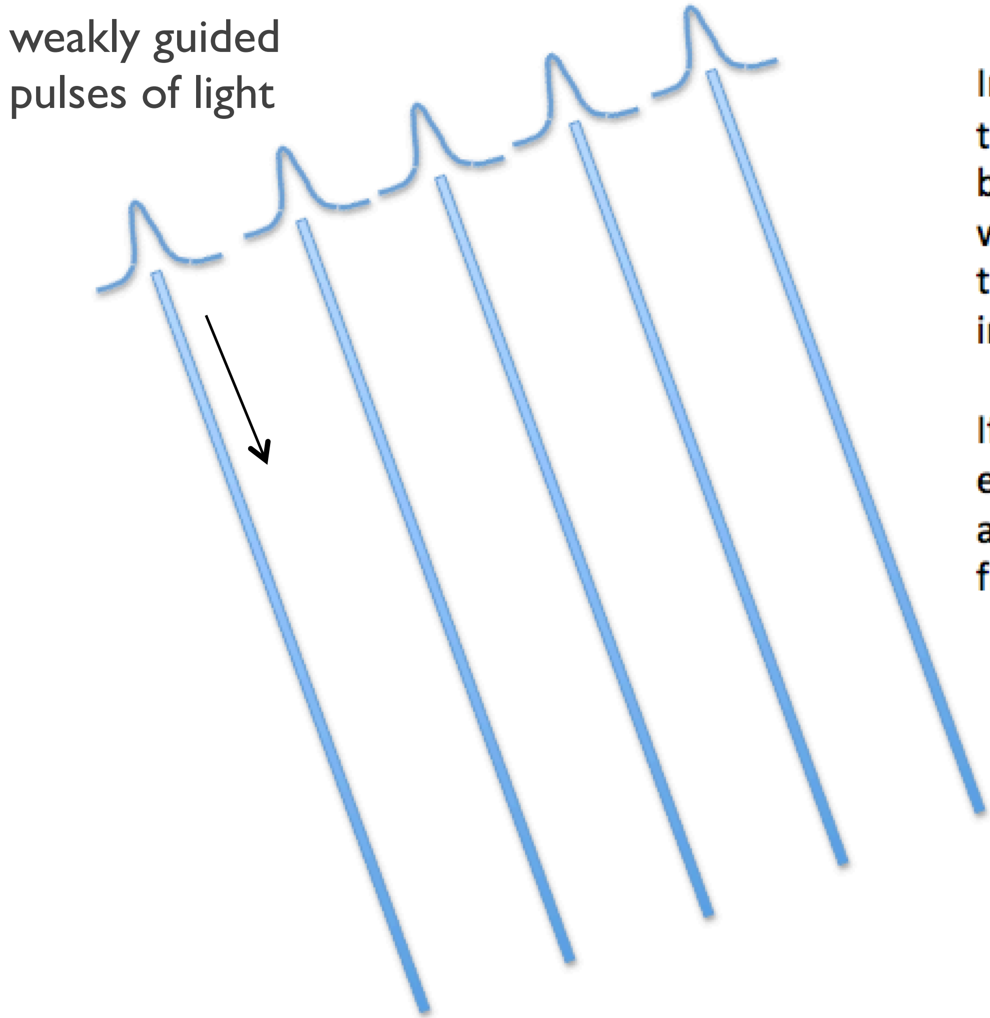
2D waveguides offer a huge range of possible functions, e.g. telecom switching stations.

But they are used almost exclusively in single mode. (People have tried few-mode waveguides, but the extra complication outweighs the benefits.)

Is there a way to exploit them with multimode fibres?

Multimode to single-mode conversion:

The photonic lantern

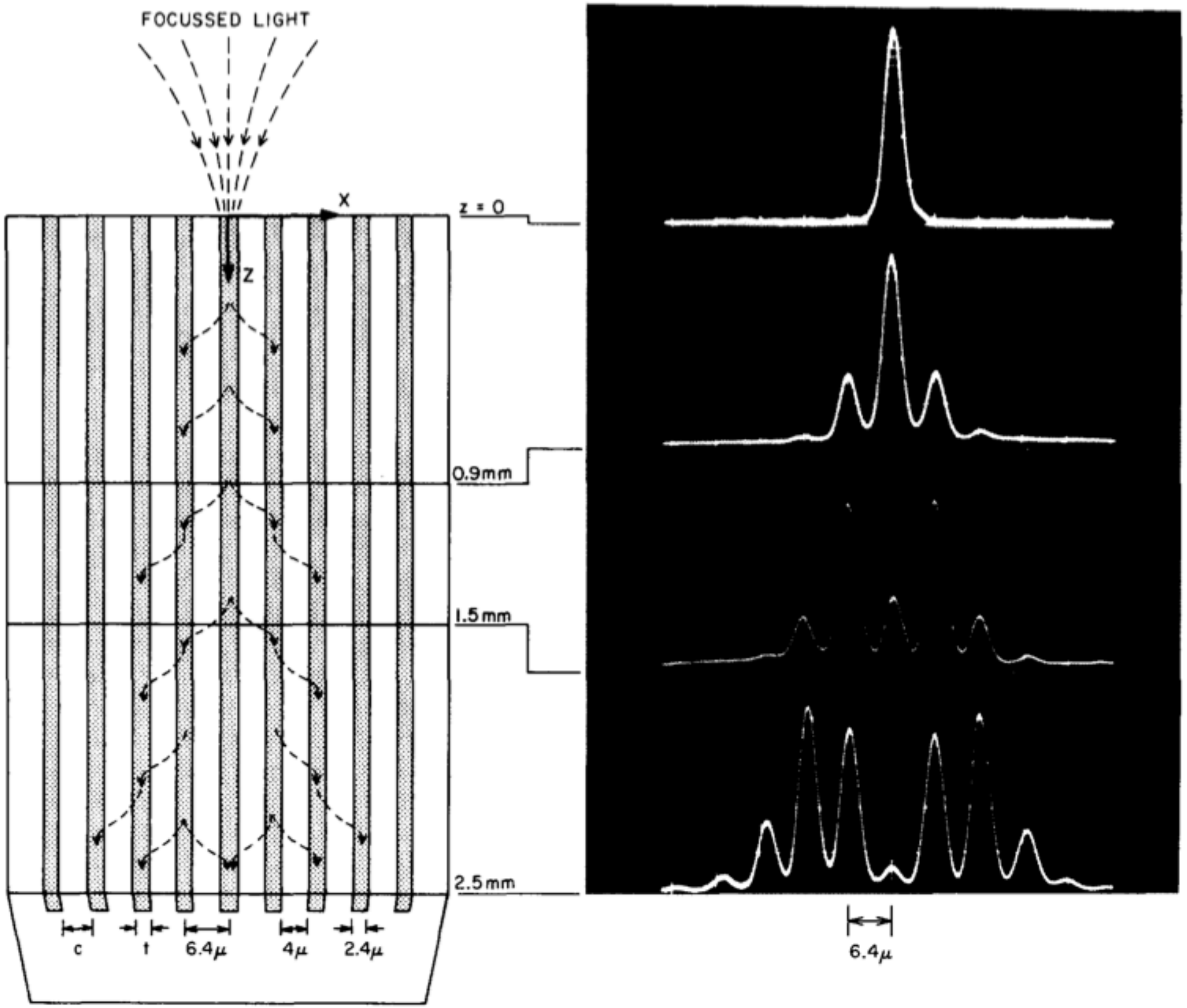


WHAT IS A SUPERMODE ?

Imagine you have 5 parallel tracks propagating 5 parallel beams of light. Assuming in the weak guiding limit such that the tracks are mutually independent.

If you bring the tracks close enough together, they behave as one entity with 5 degrees of freedom (supermodes).

Coupled tracks



(a) (b)

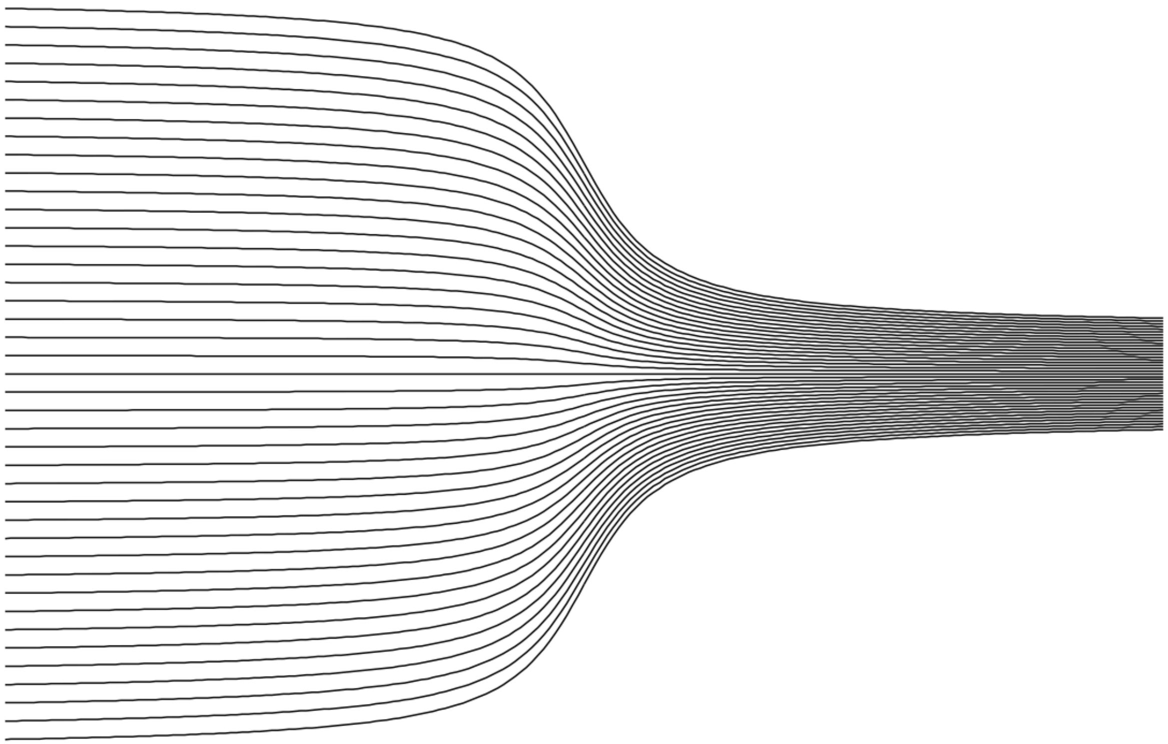
FIG. 2. (a) Sketch of channel optical waveguide directional coupler showing flow of light energy into adjacent channels. (b) Photographs of guided-light intensity profiles for various lengths. The profiles have been displayed relative to the sketch at the proper value of z. Intensity scale is arbitrary.

SUPERMODES:

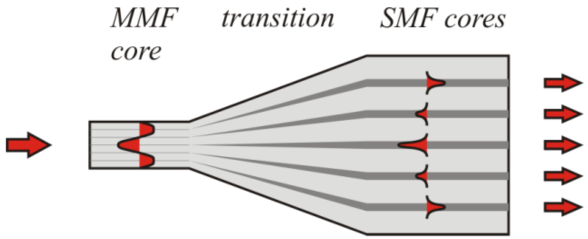
At the LHS, you might have 30 independent propagating beams in single mode.

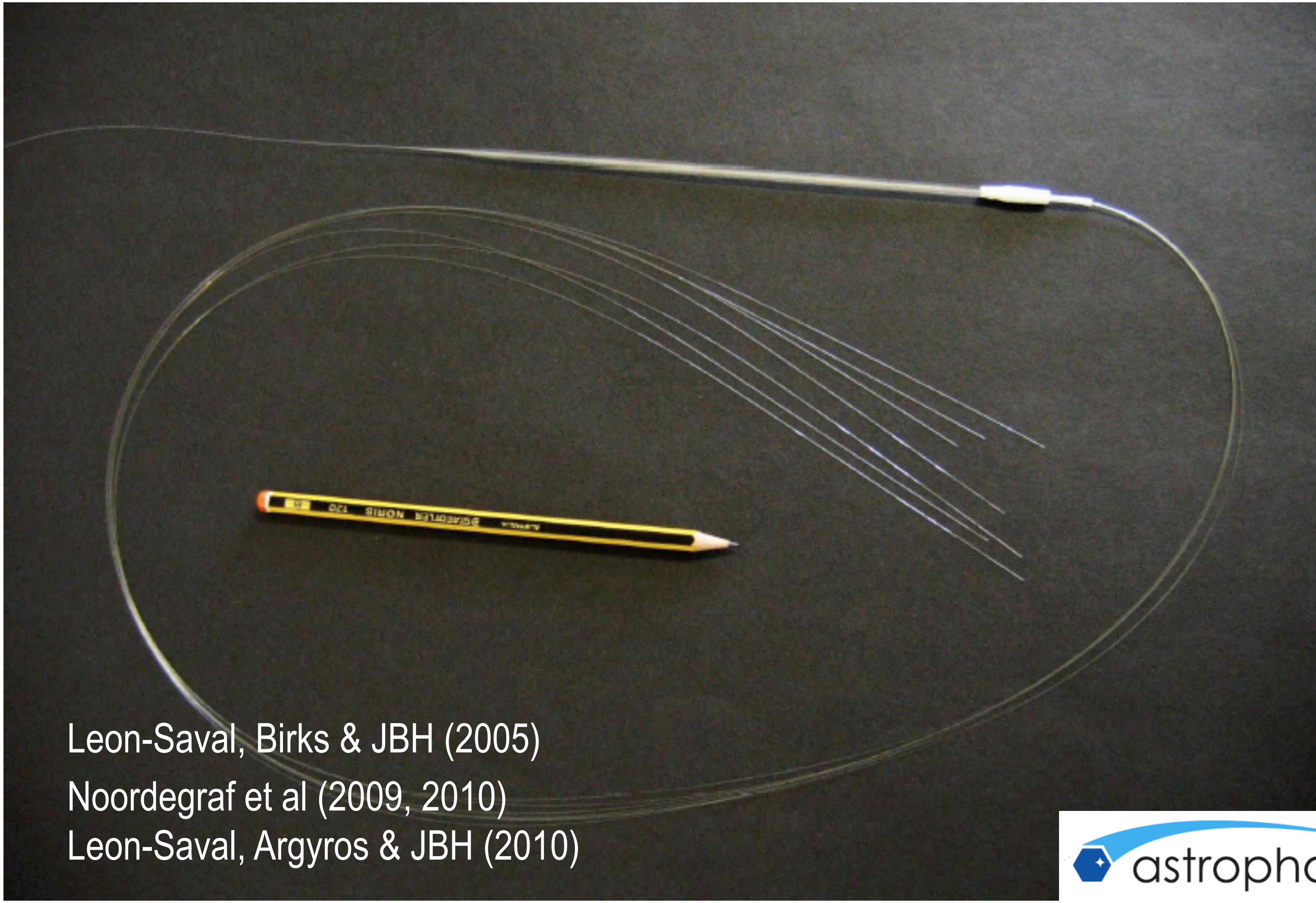
At the RHS, all 30 single modes are blended into one multimode beam comprising 30 different spatial modes (supermodes). This is a hugely important transition.

We call this the **photonic lantern** transition (3D case) – Leon-Saval et al 2005.

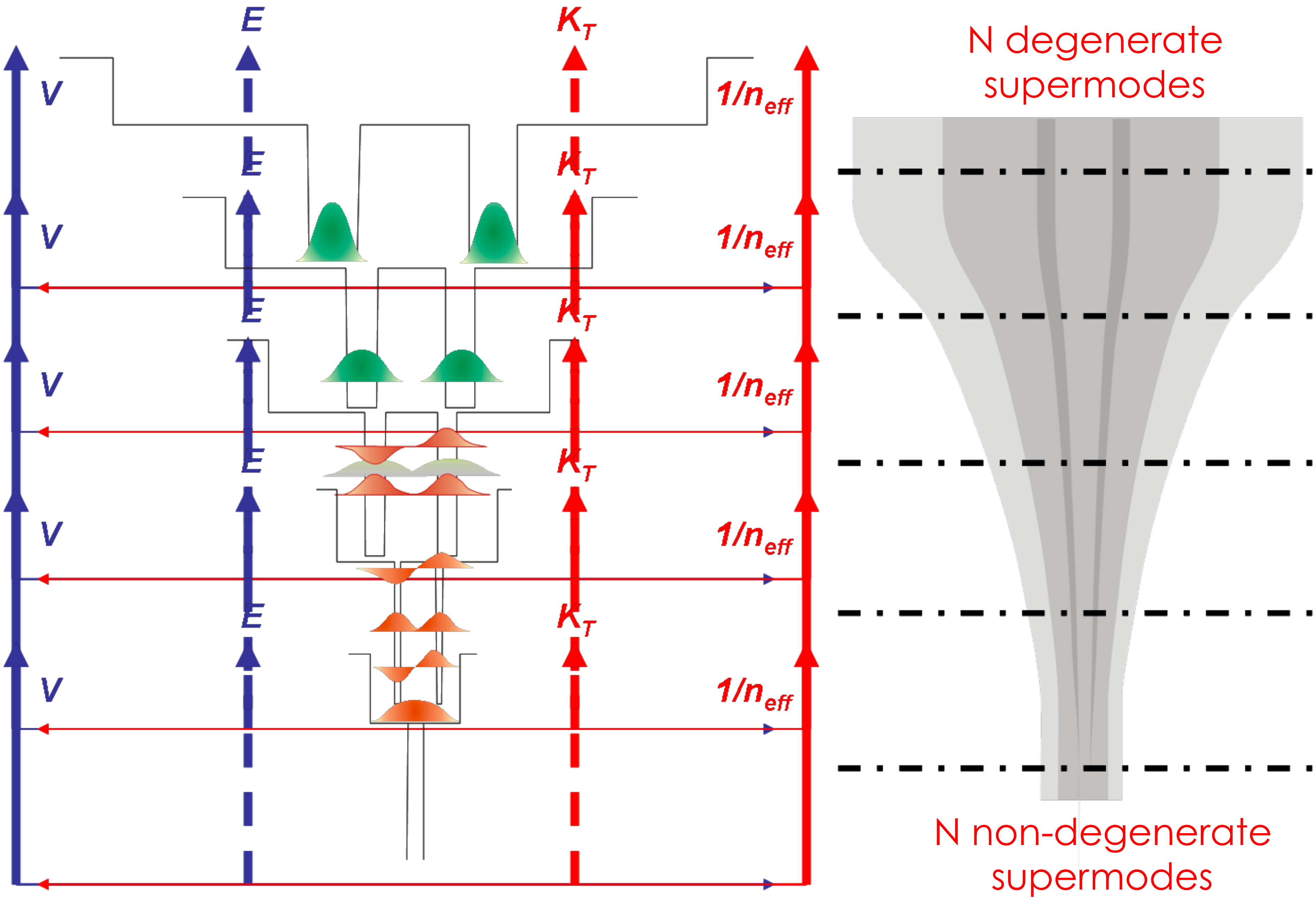


The photonic lantern: single mode action in a MMF





Photonic Lantern



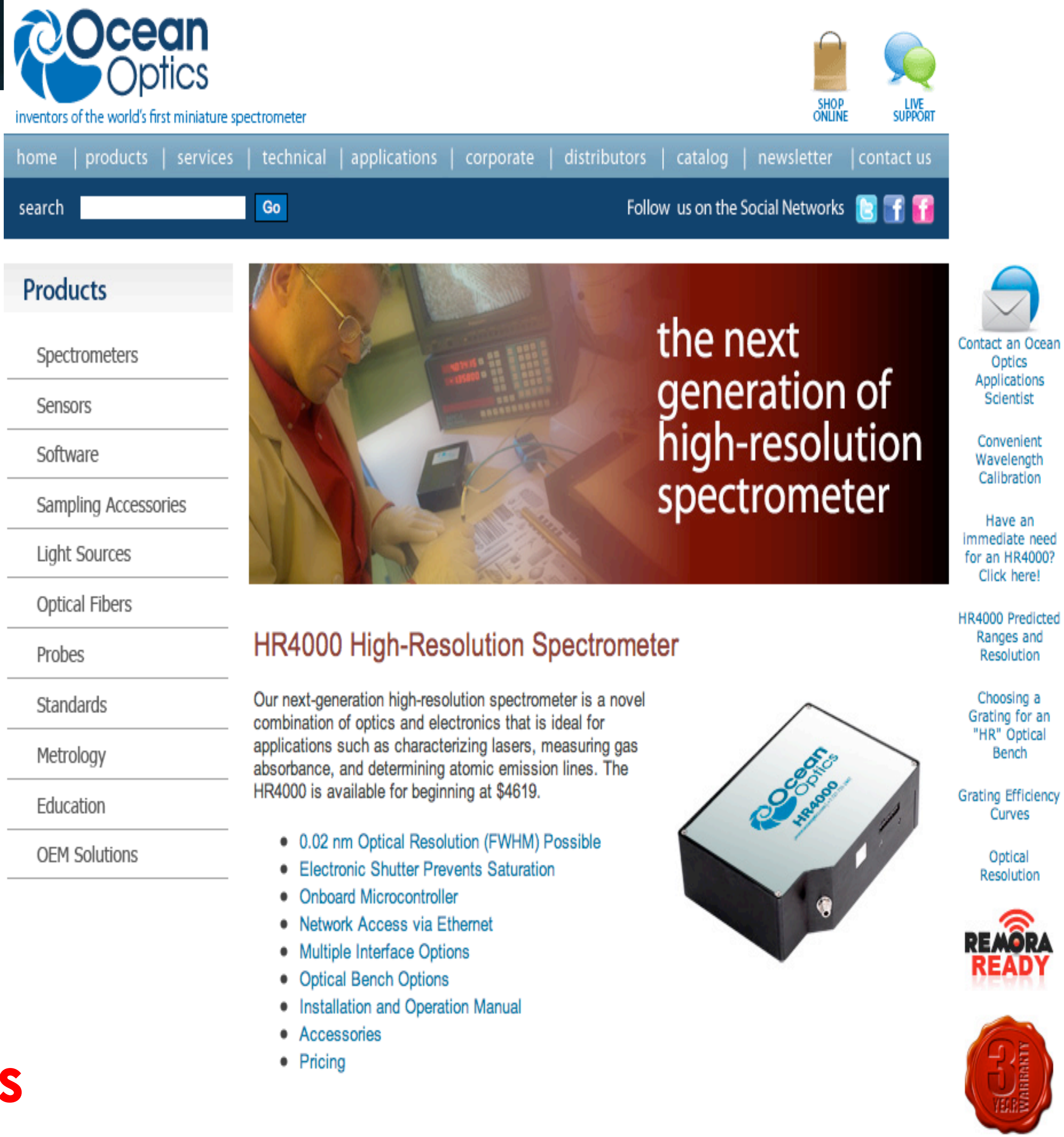
Microspectrographs:

The PIMMS concept

10% efficiency

5μm slit

$R \sim 4000$



smallest spectrographs

20% efficiency
100μm slit
$R \sim 4000$

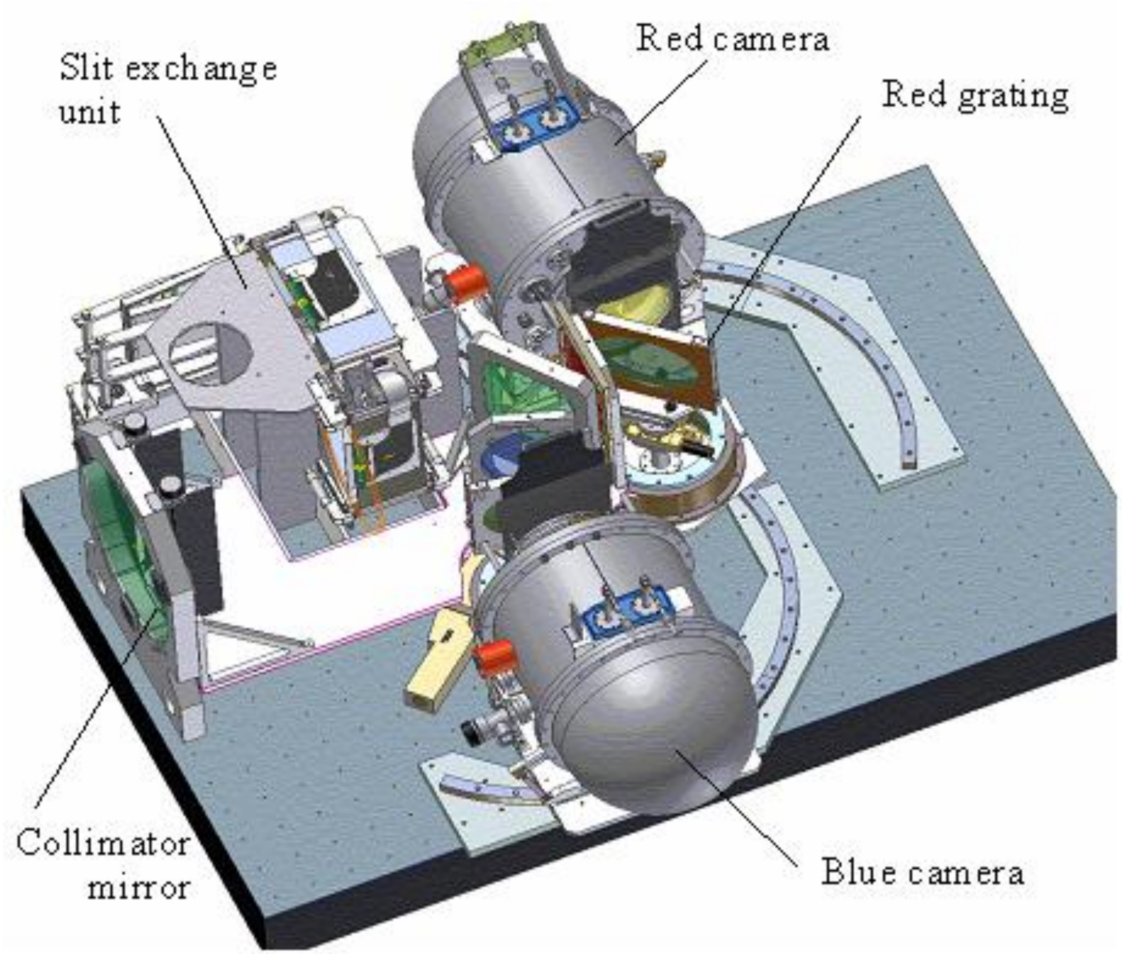


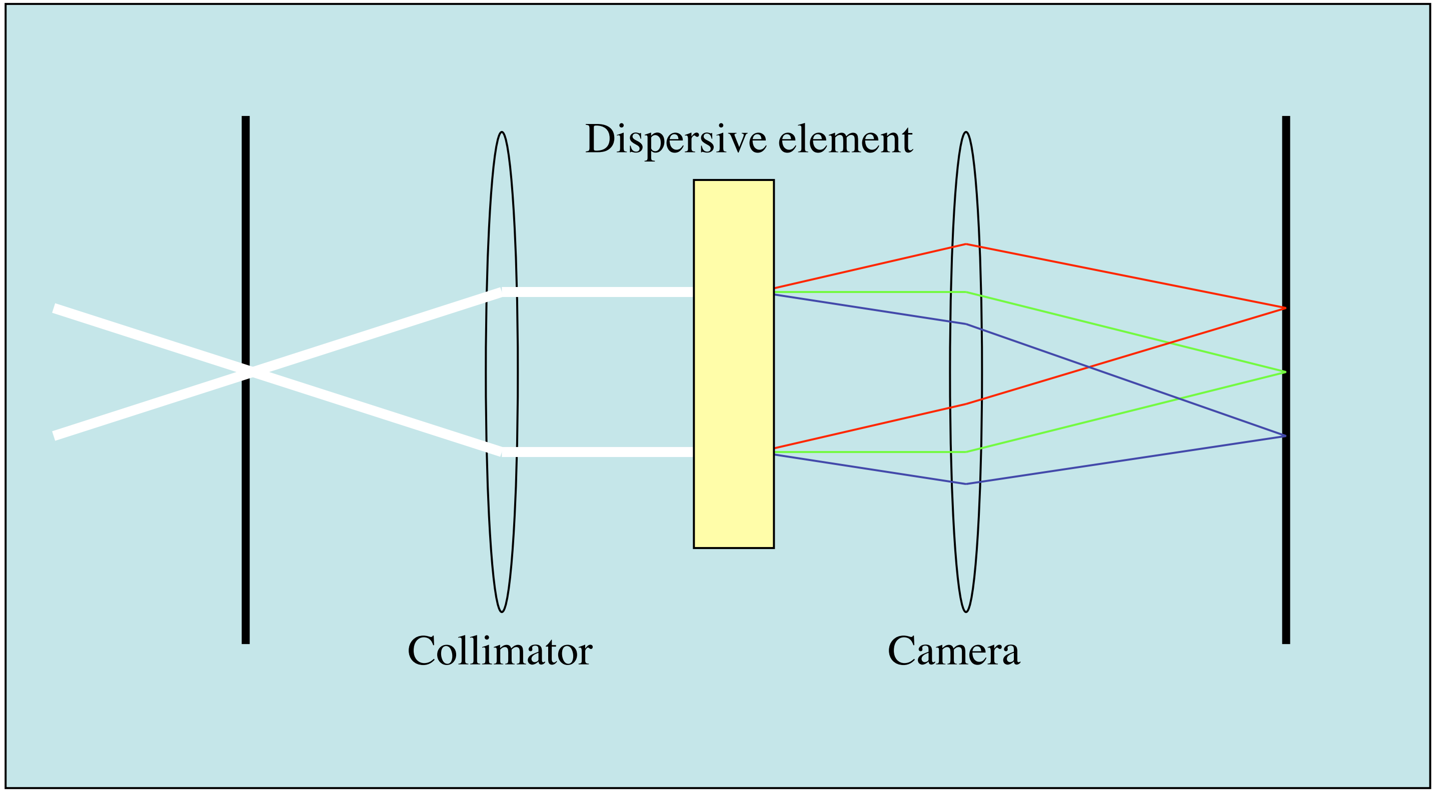
Figure 1. Physical layout of AAOmega, layout, showing the red camera in high dispersion mode, and blue camera in low dispersion mode.

largest spectrographs

Basic spectrograph: focal reducer

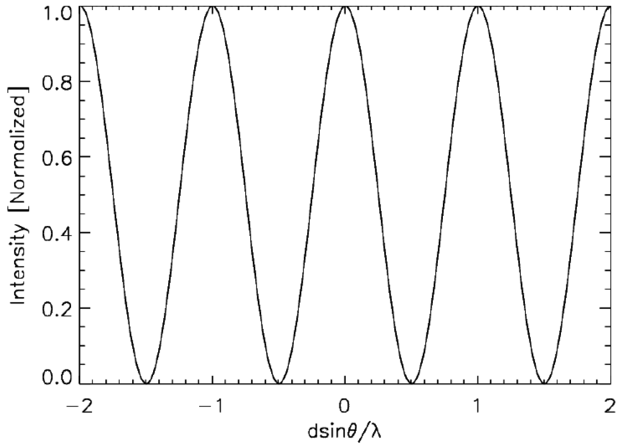
$R = m\,N$

N = no. of combining beams (finesse)

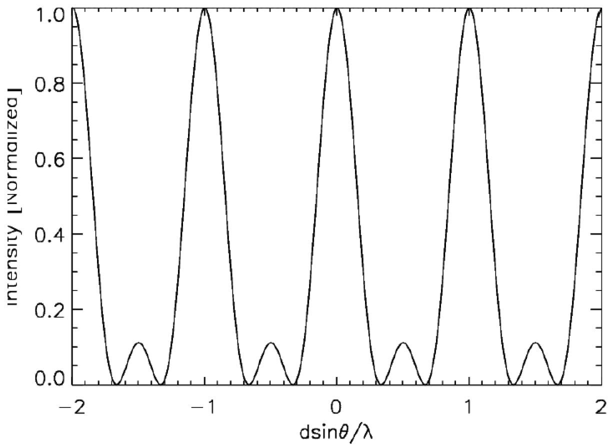


Where does R=mN come from ?

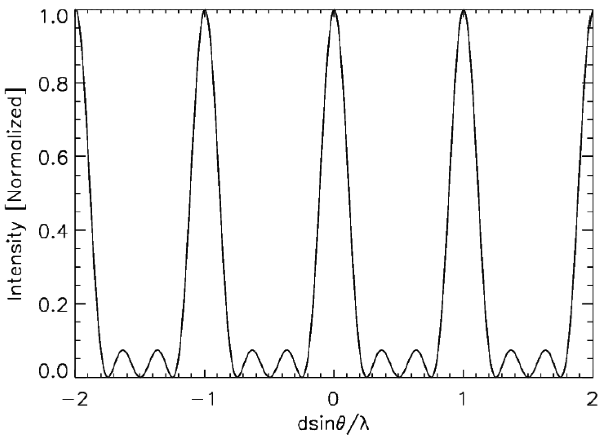
N=2



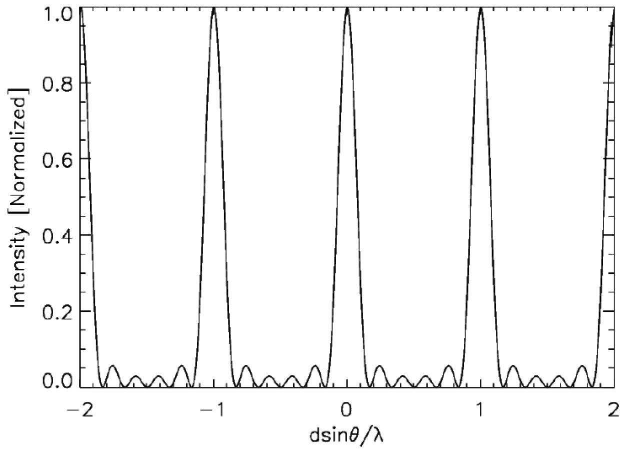
N=3



N=4



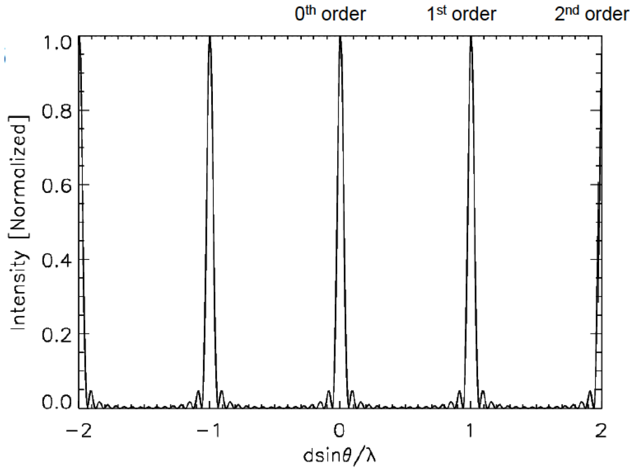
N=6



It's simply "Young's Slits" with N slits:

$$I(\theta) = \frac{I(0)}{N^2} \frac{\sin^2 N\pi d \sin\theta / \lambda}{\sin^2 \pi d \sin\theta / \lambda}$$

N=16



Why are spectrographs so far removed from the ideal?

Medium resolution spectrograph has pupil ⦸ $D_P \sim 100$ mm, say

Consider a grating with $\varrho = 1000$ lines mm^{-1}

Set $m = 1$ (tilt or prism) for straight through design

$R = m\,N = m\,D_P\,\varrho = 100{,}000$!!!

...you'd be lucky to get R=3000
at m=1 on existing instruments

A major goal of astrophotonics is to break this impasse, i.e. to collapse an instrument to its minimum configuration.

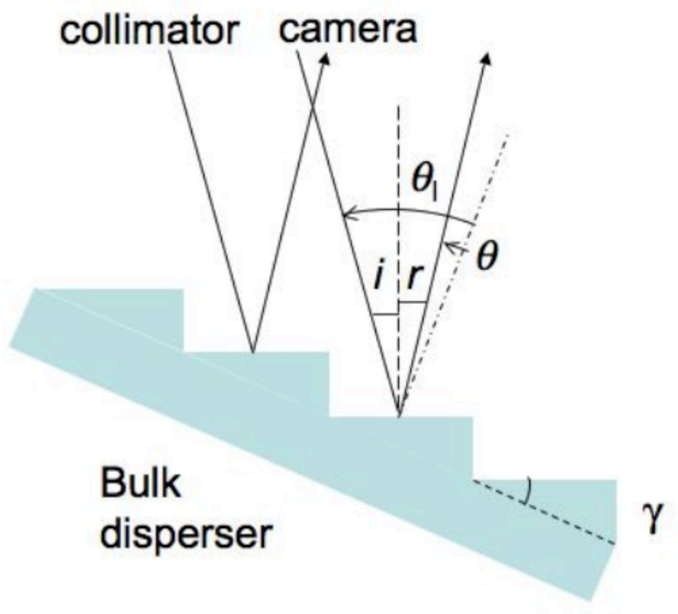
Basic spectrograph: fundamental limits

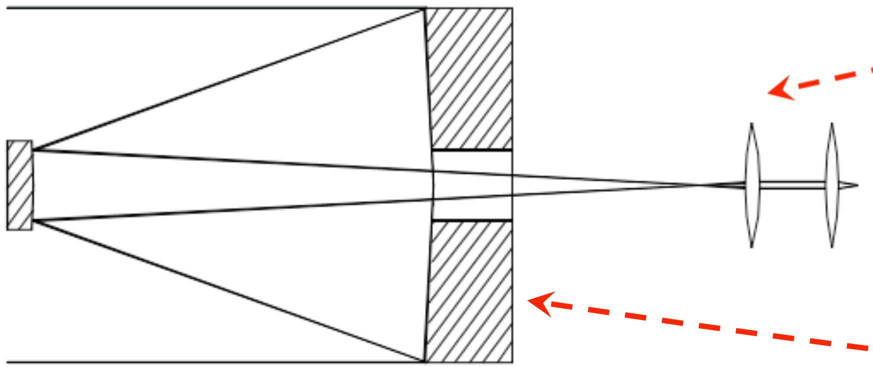
The resolution R is set by:

telescope diameter D_T
angular slit width χ
size of first element D $(\sim D_P)$

grating blaze angle γ
grating line density ϱ

beam speed f/D





$$R \equiv \frac{\lambda}{\delta\lambda} = \frac{2D\tan\gamma}{\chi D_T}$$

Basic spectrograph: cost equation

For fixed R, the cost/complexity/size equation is *at least* proportional to D_T but others find a higher power (e.g. Allington-Smith 2009).

Ignore complicating factors like beam speed f/D, illumination pattern (OTF), aberrations (a strong function of bandwidth).

So how do we achieve a minimal configuration spectrograph? i.e. **diffraction limited**, depending only on wavelength and beam speed f/D.

For all R, it needs to be independent of:

telescope diameter D_T
angular slit width χ
Illumination (natural seeing or AO)

Next slides: quick review of diffraction limited performance

Remember what a diffraction limited PSF looks like.

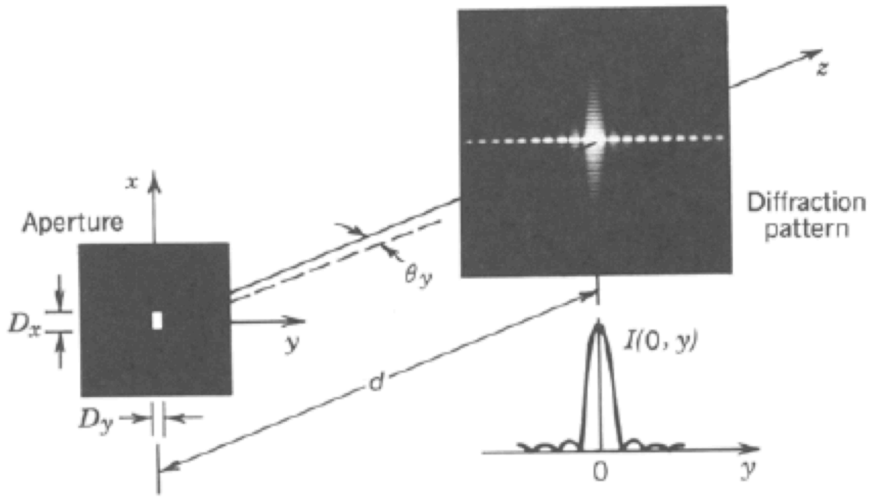


Figure 4.3-3 Fraunhofer diffraction from a rectangular aperture. The central lobe of the pattern has half-angular widths $\theta_x = \lambda/D_x$ and $\theta_y = \lambda/D_y$.

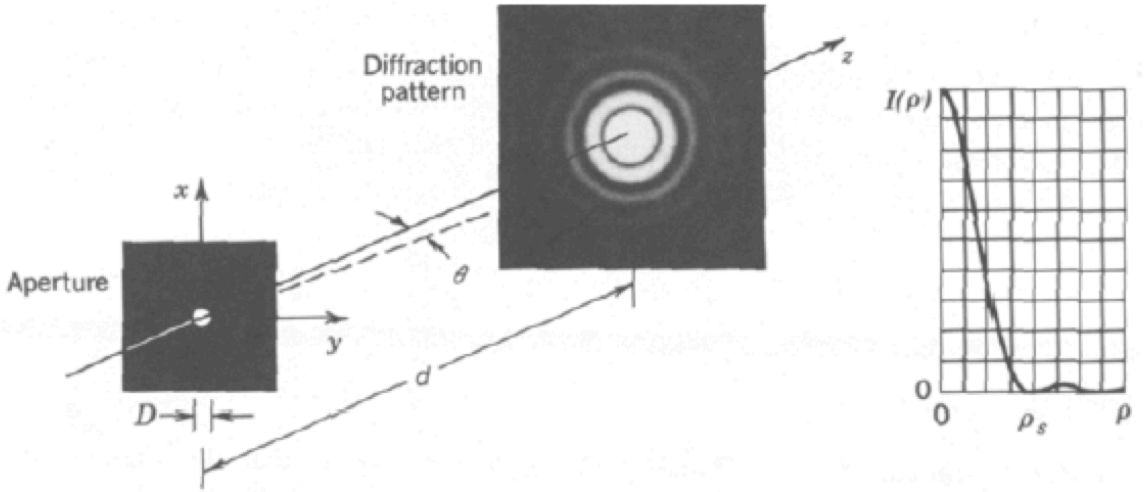
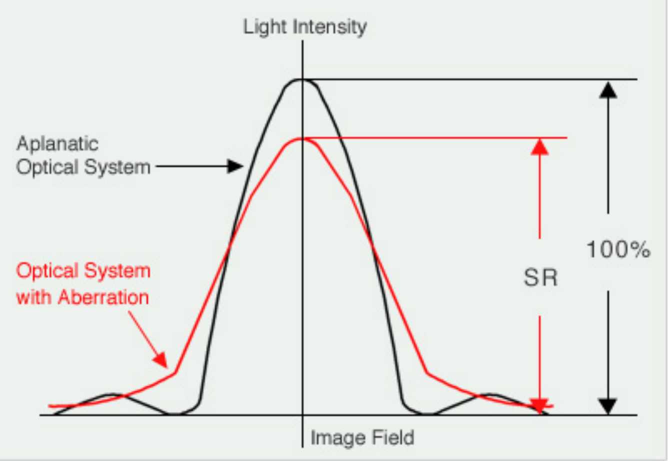


Figure 4.3-4 The Fraunhofer diffraction pattern from a circular aperture produces the Airy pattern with the radius of the central disk subtending an angle $\theta = 1.22\lambda/D$.

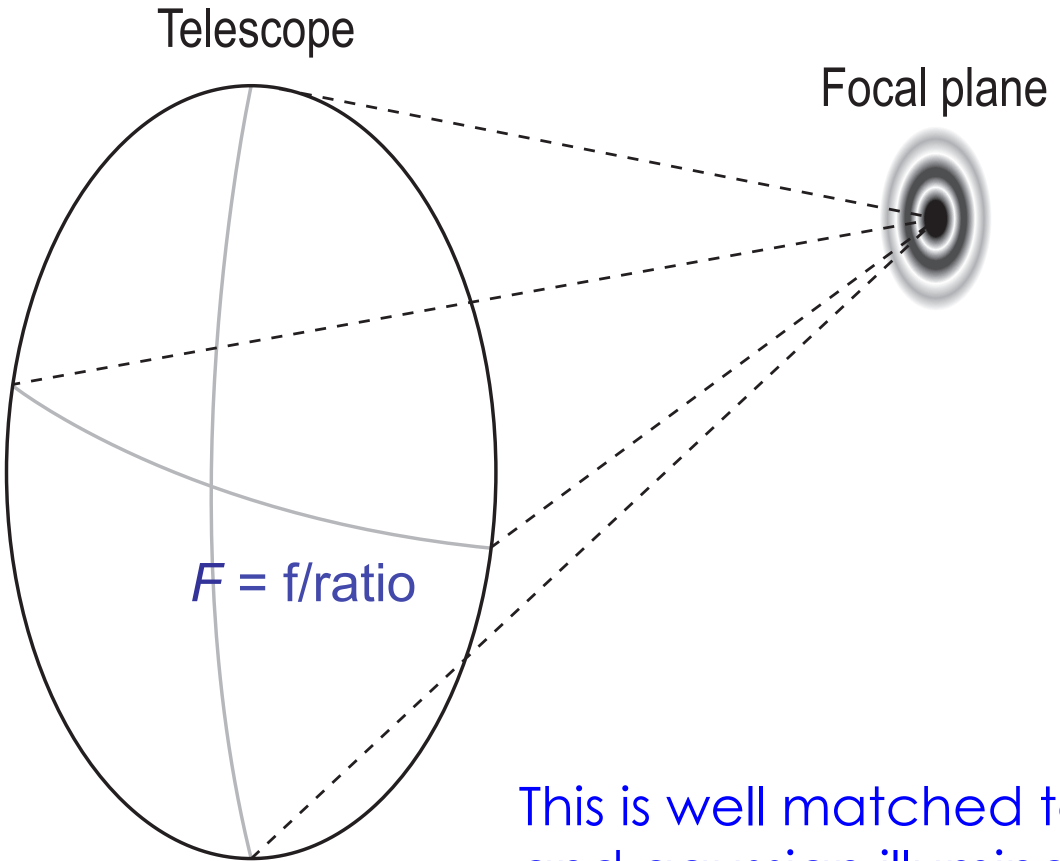
Strehl ratios: achieved vs. target



Adaptive optics tries to deliver diffraction limited performance but rarely achieves that.

	Best to date?	Target
I (900 nm)	<0.05	0.3
J (1250 nm)	0.15	0.5
H (1650 nm)	0.3	0.7
K (2200 nm)	0.7	0.9
L (3450 nm)	0.9	0.95
M (4700 nm)	0.9	0.95
N (7-14,000 nm)	0.9	0.95

Why is diffraction limited = single moded?



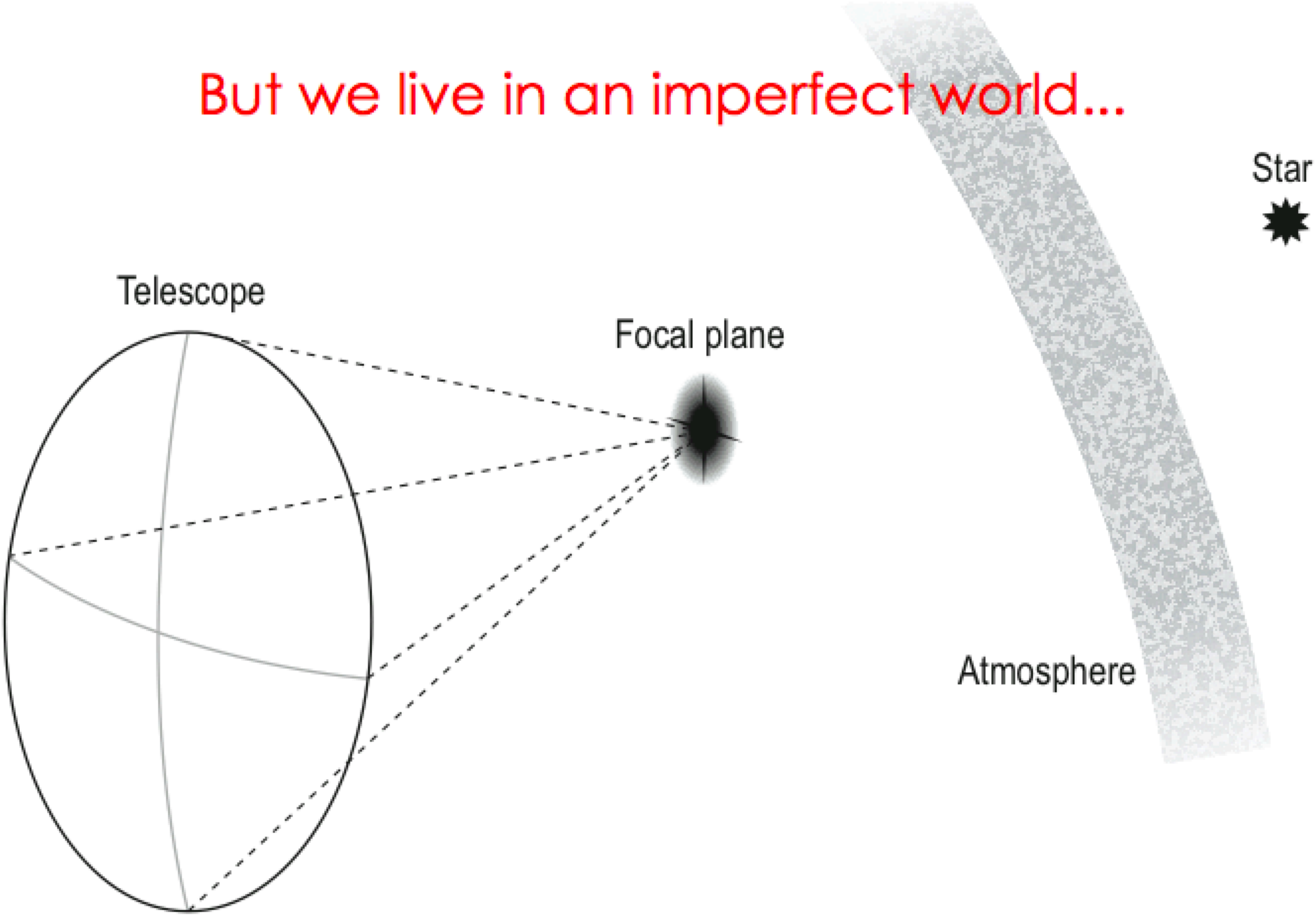
PSF diameter in microns

$$P = 1.22\lambda F$$

or 10μm at 1500nm for F=5

This is well matched to a SMF iff flat wavefront and gaussian illumination. Spatial modes M=1.

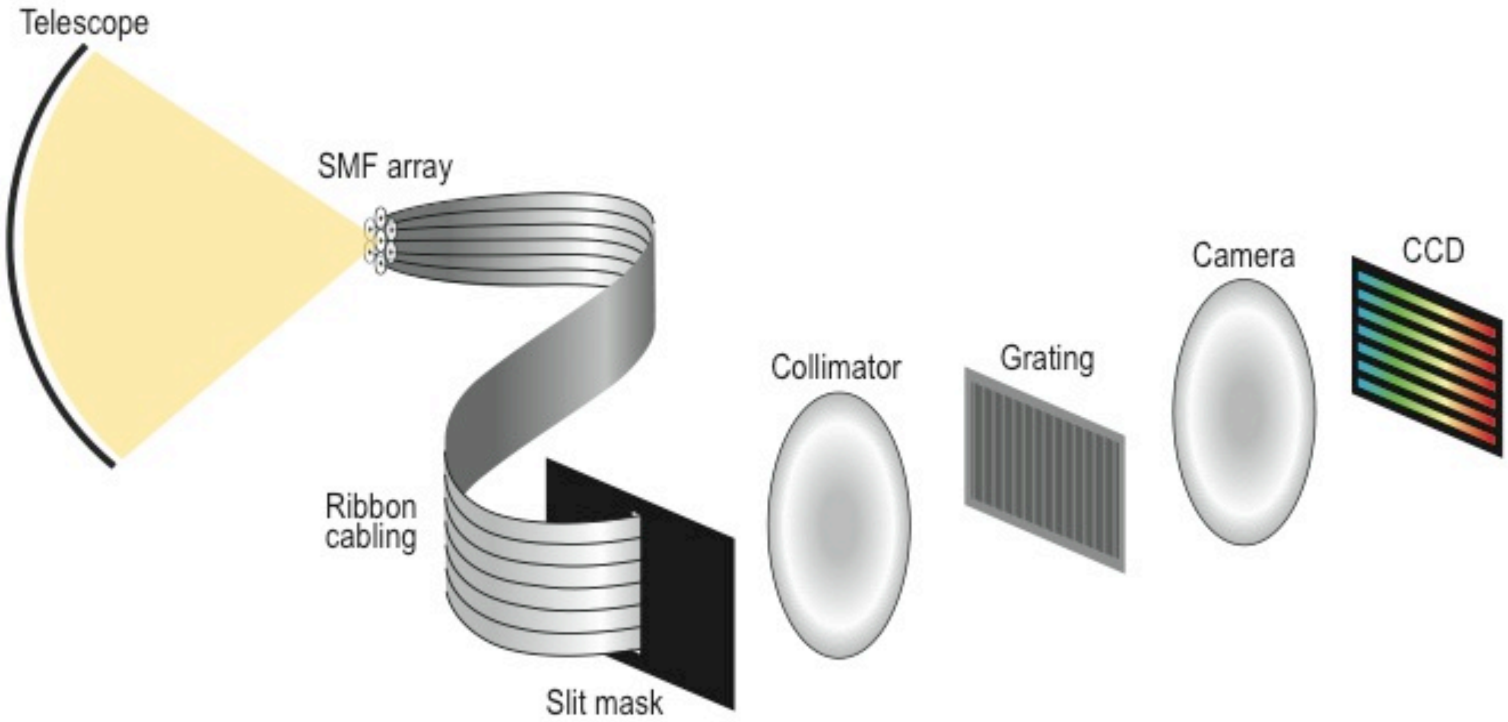
But we live in an imperfect world...



Telescope PSF is imperfect gaussian such that $M >> 0$

Horton & JBH 2006, Corbett 2007

A very inefficient spectrograph concept



How many unpolarized transverse modes do we need for efficient MMF coupling?

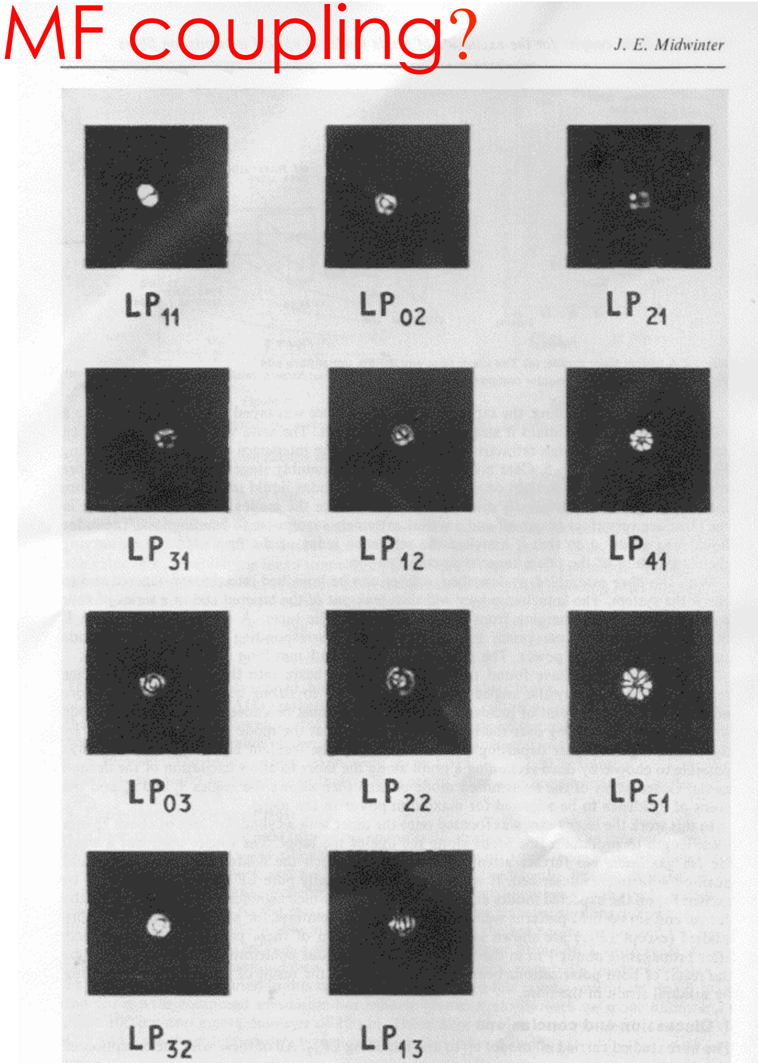
Number of modes, M

$$M \approx \frac{V^2}{4} \qquad V = \frac{\pi D}{\lambda} NA$$

D=80µm core, NA=0.1, λ=1500 nm

$\Rightarrow$ $\mathbf{M = 61}$

n.b. mode conservation is equivalent to étendue (AΩ)



Without AO, we need 40-80 modes to cover near IR, more in optical

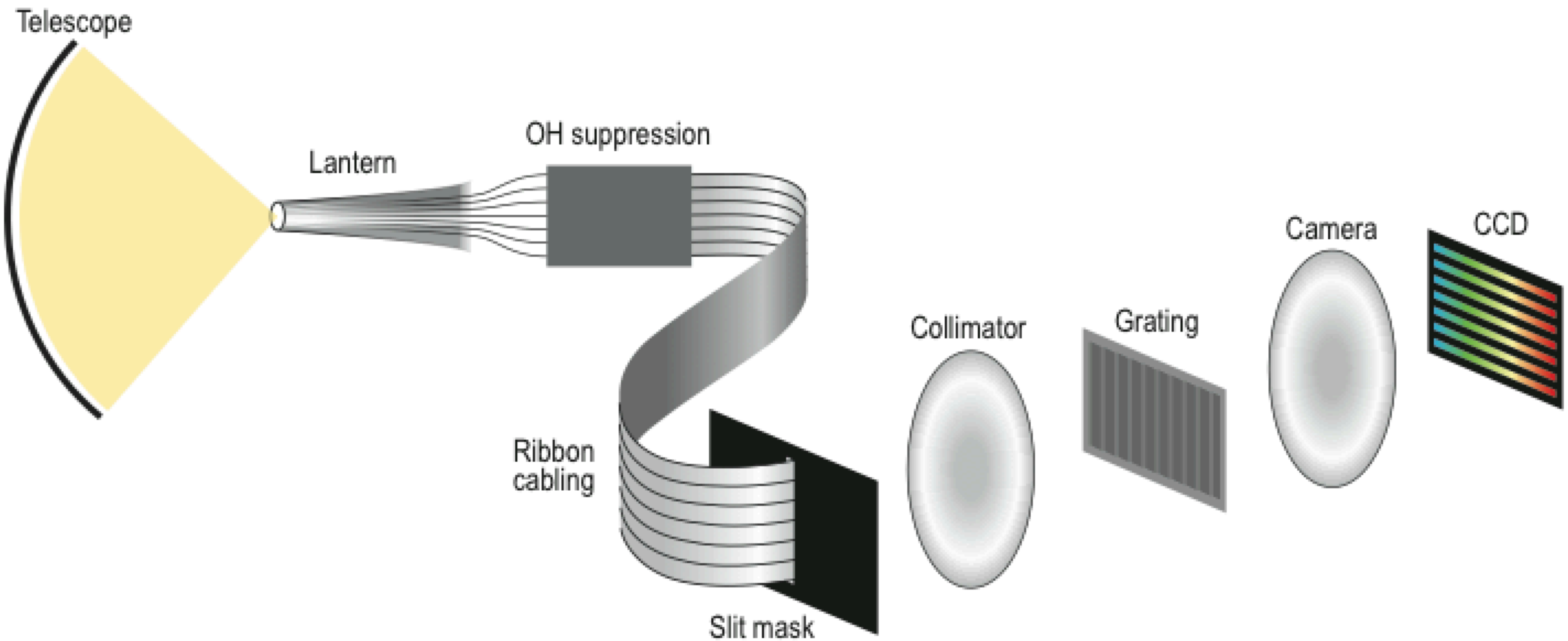
With AO, maybe 7 modes ok? (Horton & JBH 2007) – depends on Strehl ratio

For mainstream astronomy, we need photonic action in a multimode fibre

How is this possible?

The photonic lantern

PIMMS #0 = "shoebox spectrograph"



The optical system is **always** diffraction limited **regardless of input** which leads us to a remarkable conclusion.

The University of Sydney

10% efficiency
5µm slit
R ~ 4000

PIMMS:
70% efficiency
Any slit
R ~ 4000

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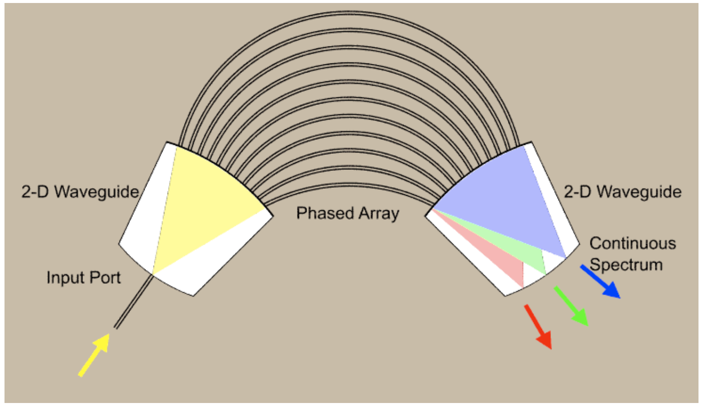
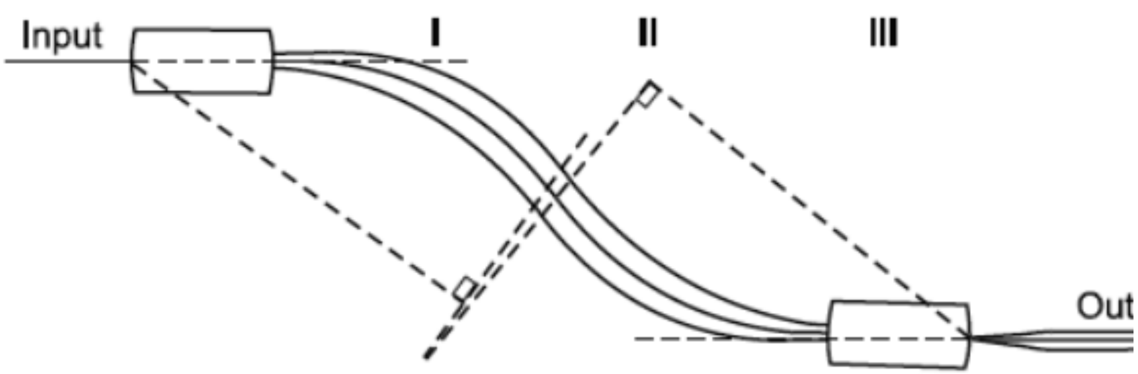
REMORA READY

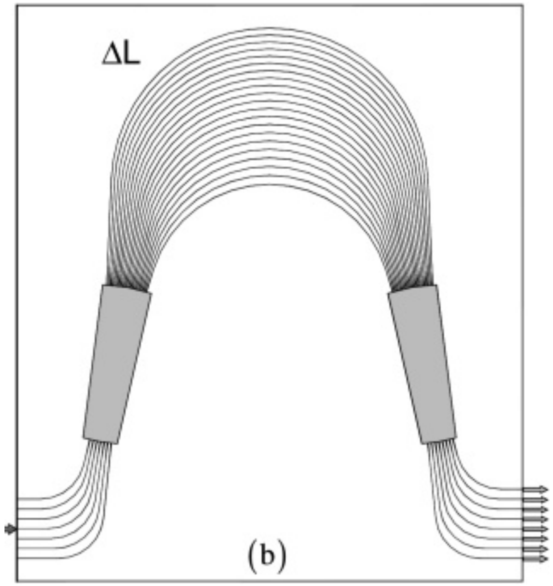
The case for a fully photonic device:

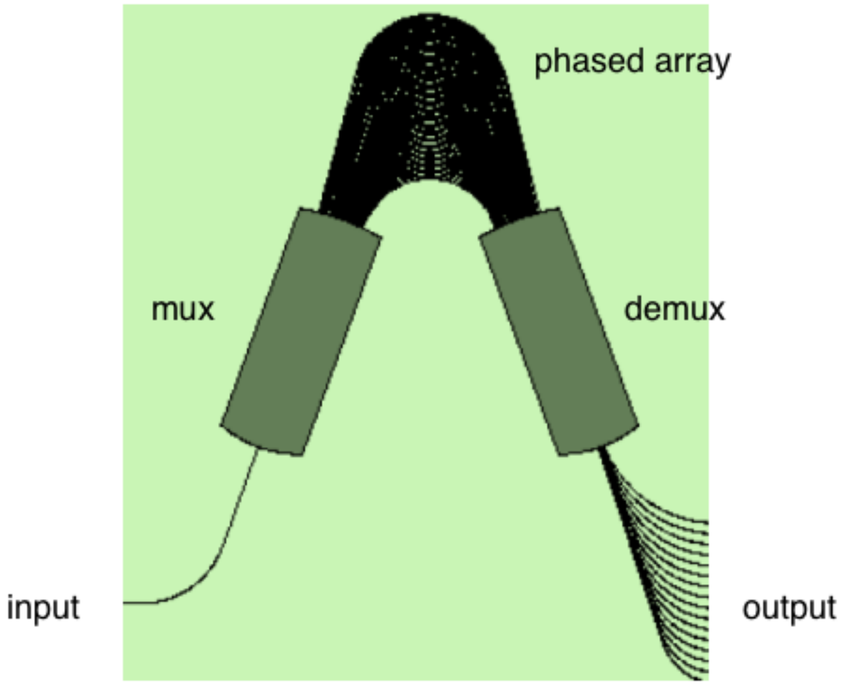
"the vanishing spectrograph"

Array Waveguide Grating









Integrated photonic spectrograph

Instruments without optics: an integrated photonic spectrograph

J. Bland-Hawthorn[a], A. Horton
Anglo-Australian Observatory, 167 Vimiera Rd, Eastwood, NSW 2122, Australia

2006

We explore the use of **array waveguide gratings** and **photonic echelle gratings** integrated onto a chip.

Typical device working at R ~ 4000, say, will be 4 cm in size.

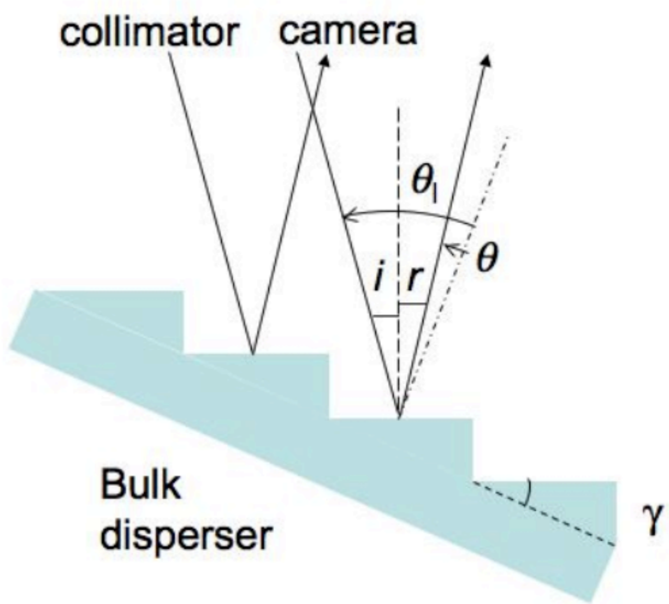
Each circuit is fed by a single-mode fibre.

The light on exit is dispersed onto a detector array.

Basic Spectrograph: Grating theory

Scattering centres with line density $\boldsymbol{\rho}$ and extra path difference $\boldsymbol{q}$

$$\sin\theta + \sin\theta_I = (m\lambda + q)\rho$$



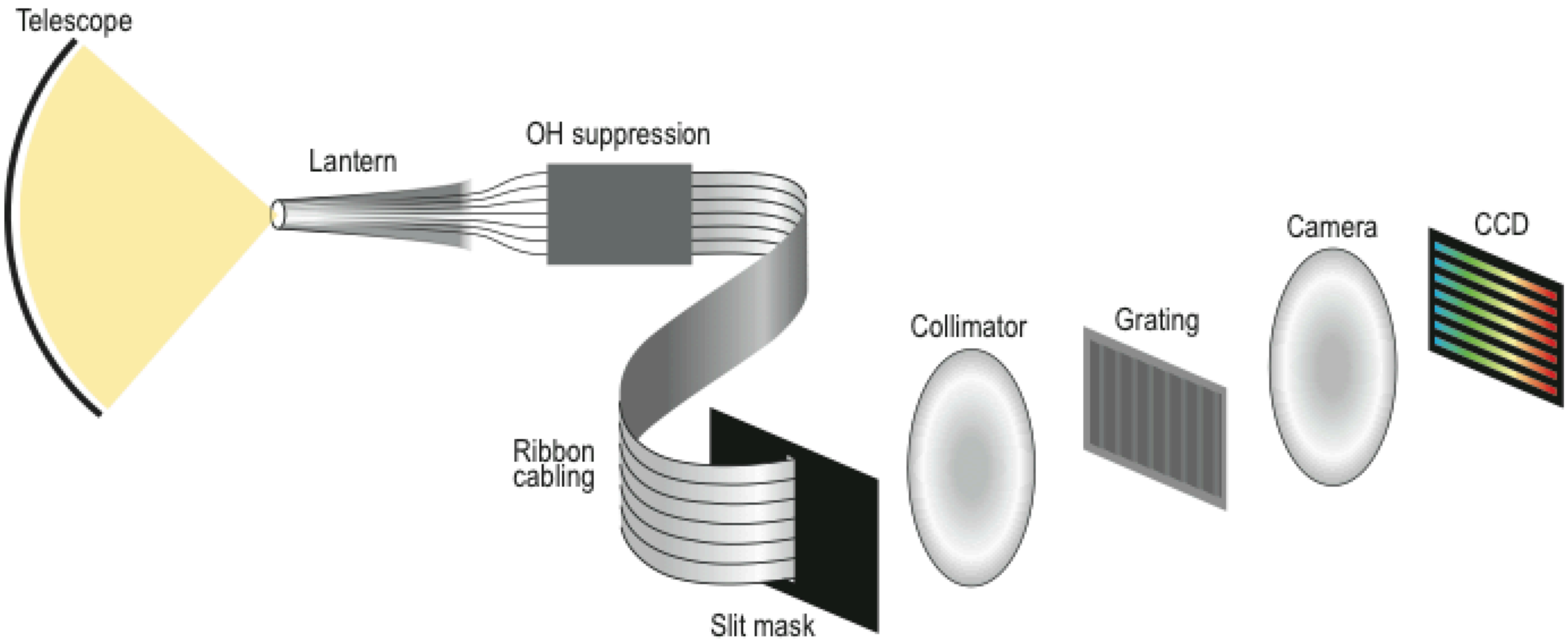
Angular dispersion independent of $\boldsymbol{q}$

$$\Delta \equiv \frac{d\lambda}{d\theta} = \frac{\cos\theta}{m\rho}$$

For conventional gratings, $\boldsymbol{q=0}$

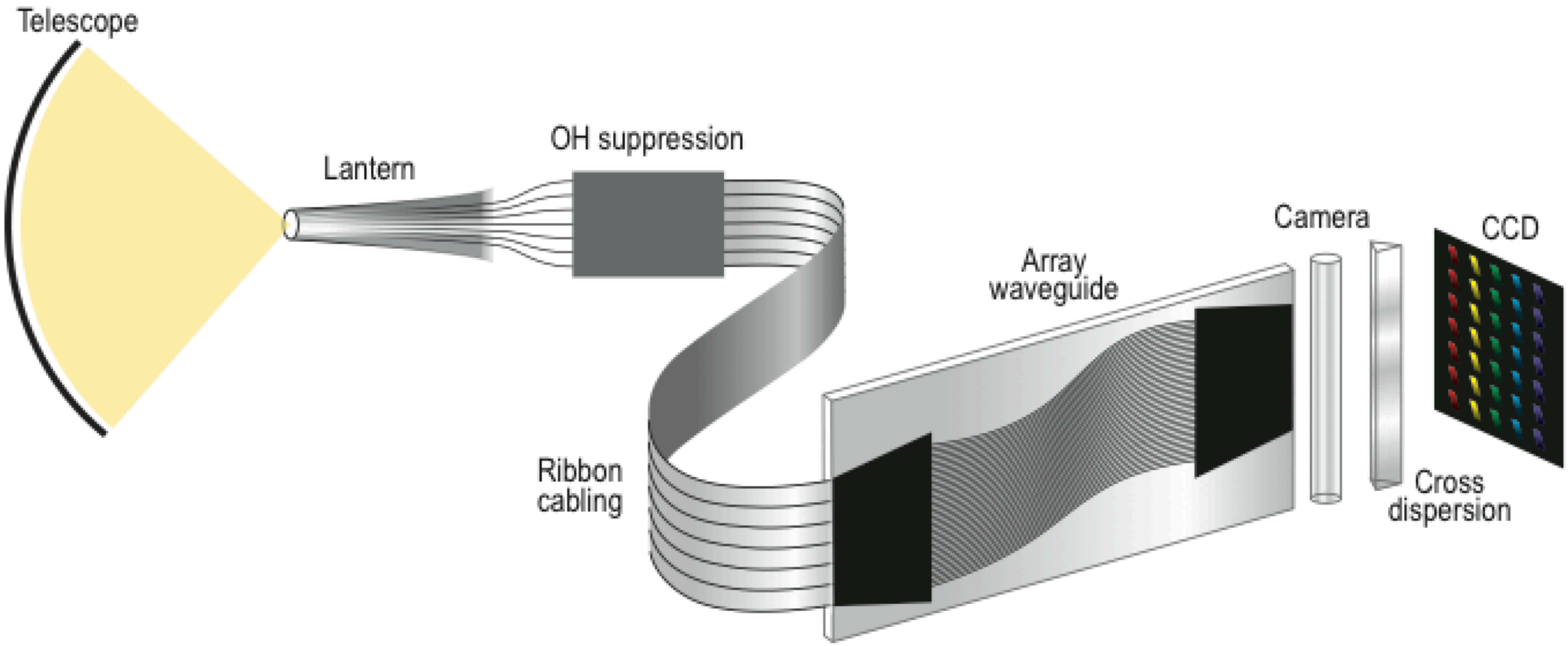
...we will meet non-zero $\boldsymbol{q}$ later

So we go from this configuration...



to this configuration...

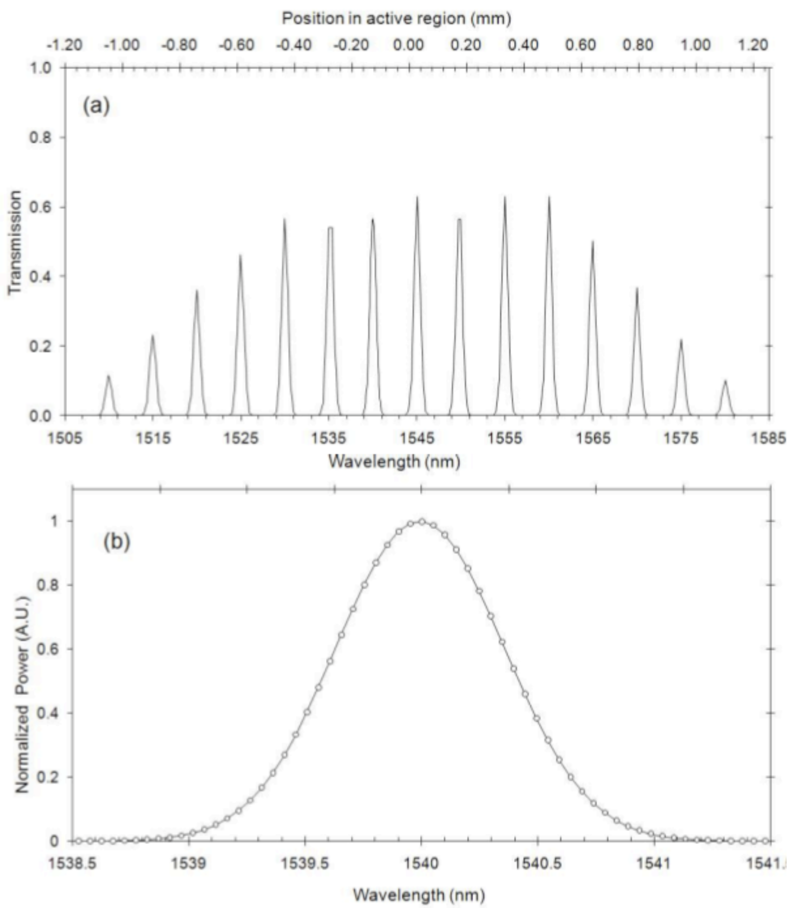
PIMMS #1

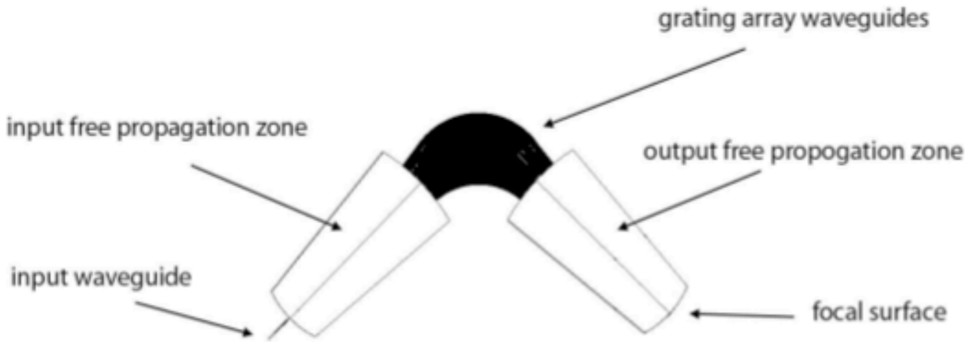


The optical system is **always** diffraction limited **regardless of input** which leads us to a remarkable conclusion.

First device

JBH et al 2007
Cvetojevic et al 2009

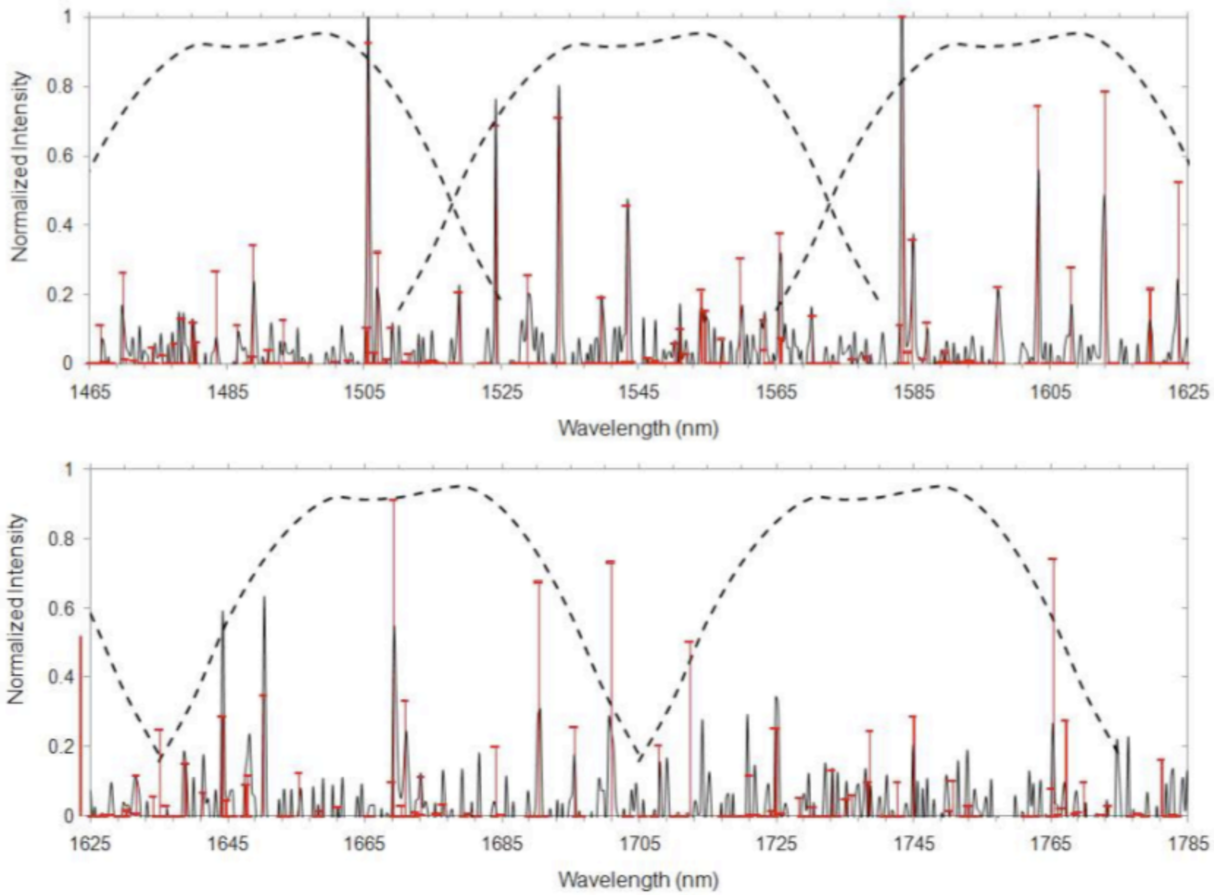




R=2000, 4000, 7000

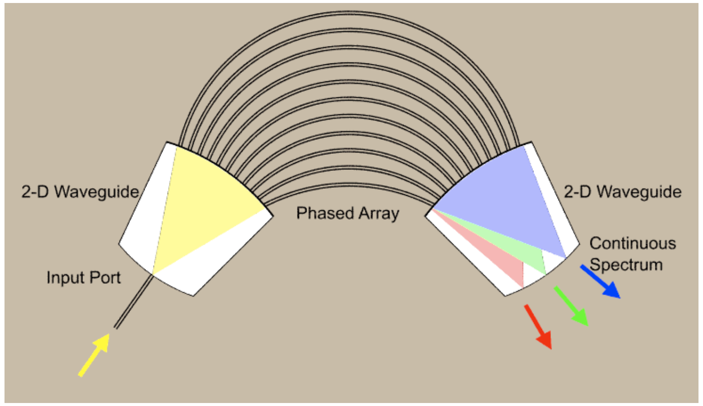
Characterization and on-sky demonstration of an integrated photonic spectrograph for astronomy 2009

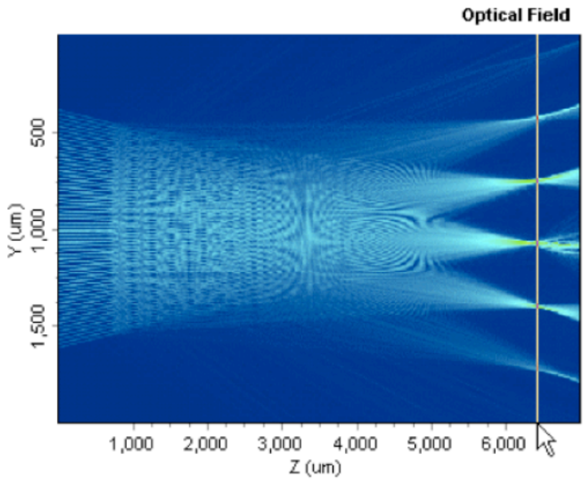
N. Cvetojevic,[1] J. S. Lawrence,[1,2,*] S. C. Ellis, [3] J. Bland-Hawthorn,[3] R. Haynes,[1] and A. Horton[1]

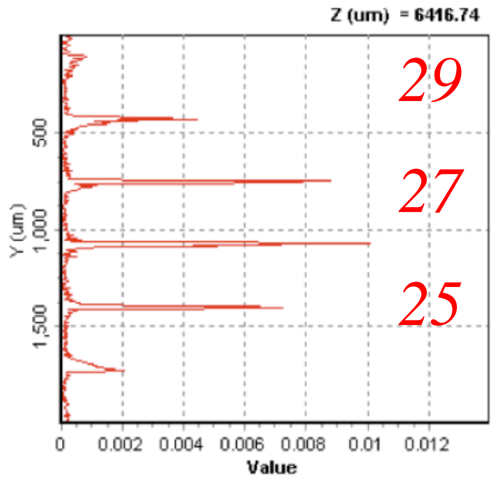


The first ever continuous spectrum from an IPS !

Cross dispersion



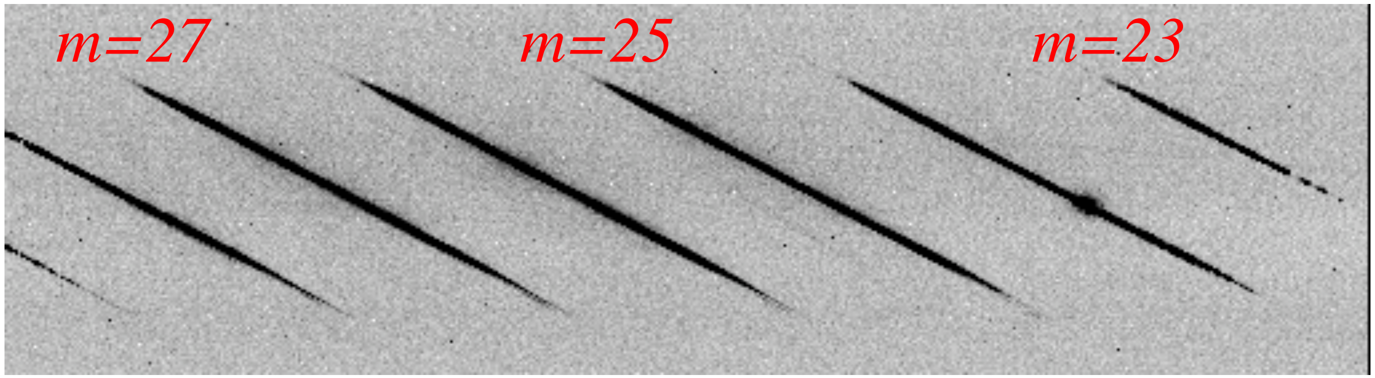




$$m\lambda = const$$

$$R = mN$$

$$\Delta\lambda = \frac{\lambda}{m+1}$$



Beating the classical limit: A diffraction-limited spectrograph for an arbitrary input beam

Christopher H. Betters,[1,2,*] Sergio G. Leon-Saval,[1] J. Gordon Robertson,[1,2] and Joss Bland-Hawthorn[1,2]

[1] *Institute of Photonics and Optical Science, School of Physics, University of Sydney, 2006, Australia*
[2] *Sydney Institute for Astronomy, School of Physics, University of Sydney, 2006, Australia*
[*] *c.betters@physics.usyd.edu.au*

Abstract: We demonstrate a new approach to classical fiber-fed spectroscopy. Our method is to use a photonic lantern that converts an arbitrary (e.g. incoherent) input beam into *N* diffraction-limited outputs. For the highest throughput, the number of outputs must be matched to the total number of unpolarized spatial modes on input. This approach has many advantages: (i) after the lantern, the instrument is constructed from 'commercial off the shelf' components; (ii) the instrument is the minimum size and mass configuration at a fixed resolving power and spectral order; (iii) the throughput is better than 60% (slit to detector, including detector QE of ~80%); (iv) the scattered light at the detector can be less than 0.1% (total power). Our first implementation operates over 1545-1555 nm (limited by the detector) with a spectral resolution of 0.055nm (*R*~30,000) using a 1 × 7 (1 multi-mode input to 7 single-mode outputs) photonic lantern. This approach is a first step towards a fully integrated, multimode photonic microspectrograph.

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OCIS codes: (350.1260) Astronomical optics; (300.6190) Spectrometers; (060.2430) Fibers, single-mode; (060.2350) Fiber optics imaging.

Optics Express
2013

References and links

1. J. Bland-Hawthorn, J. Lawrence, G. Robertson, S. Campbell, B. Pope, C. Betters, S. Leon-Saval, T. Birks, R. Haynes, N. Cvetojevic, and N. Jovanovic, "PIMMS: photonic integrated multimode microspectrograph," Proc. SPIE **7735**, 77350N, 77350N-9 (2010).
2. S. G. Leon-Saval, A. Argyros, and J. Bland-Hawthorn, "Photonic lanterns: a study of light propagation in multimode to single-mode converters," Opt. Express **18**(8), 8430–8439 (2010).
3. S. G. Leon-Saval, T. A. Birks, J. Bland-Hawthorn, and M. Englund, "Multimode fiber devices with single-mode performance," Opt. Lett. **30**(19), 2545–2547 (2005).
4. D. Noordegraaf, P. M. W. Skovgaard, R. H. Sandberg, M. D. Maack, J. Bland-Hawthorn, J. S. Lawrence, and J.

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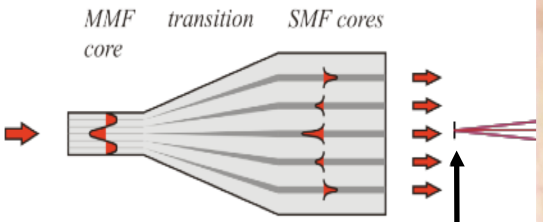
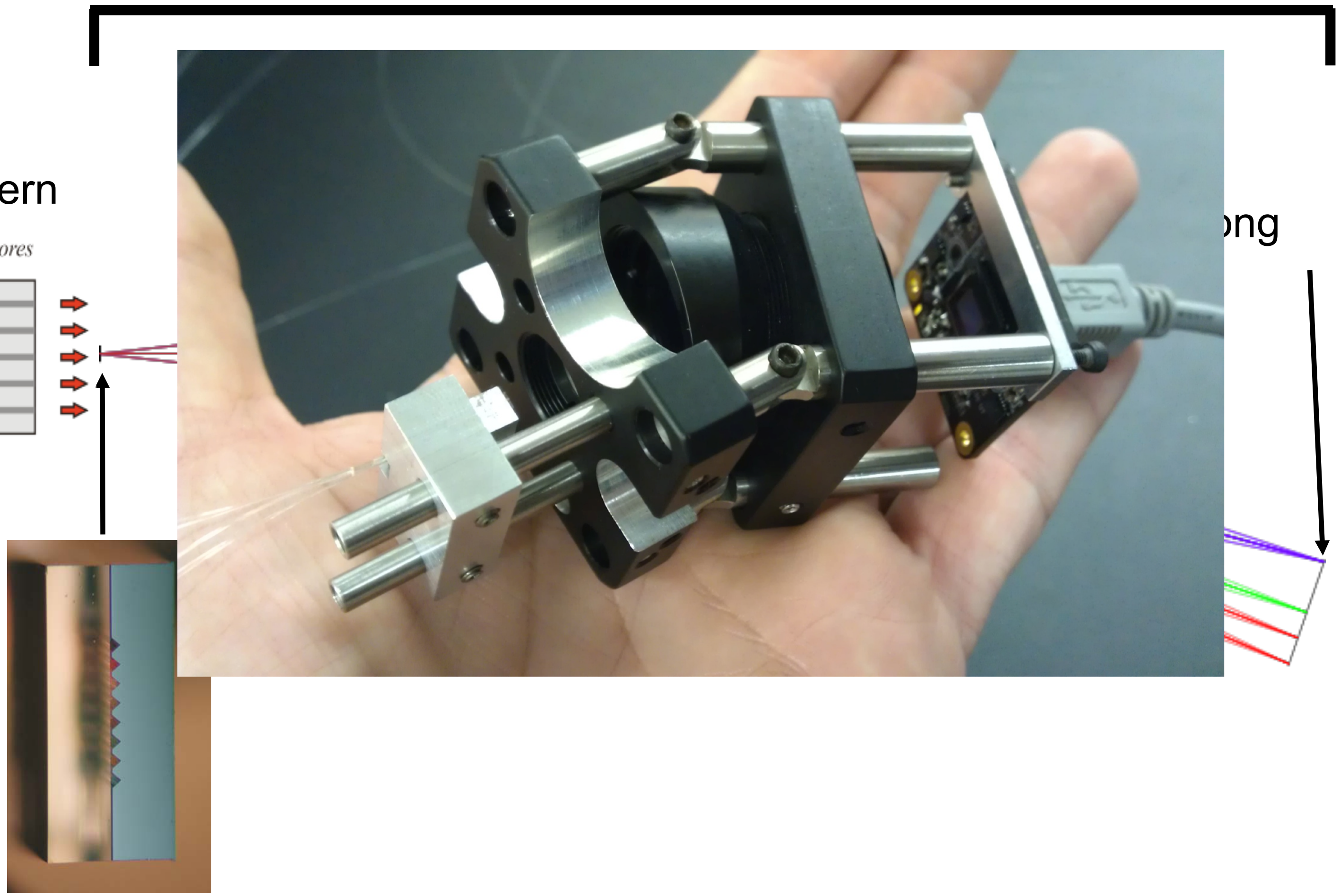
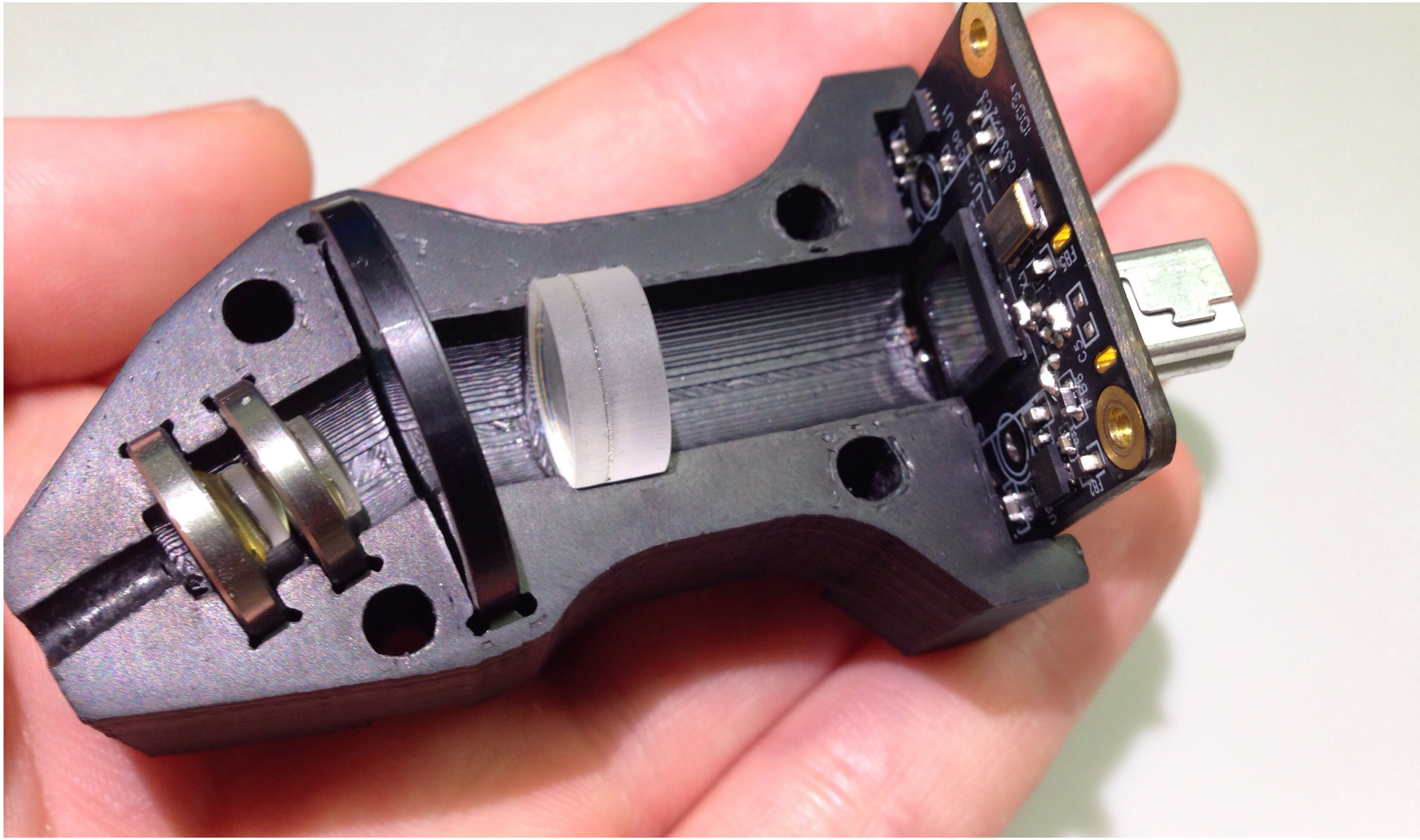
Photonic Lantern



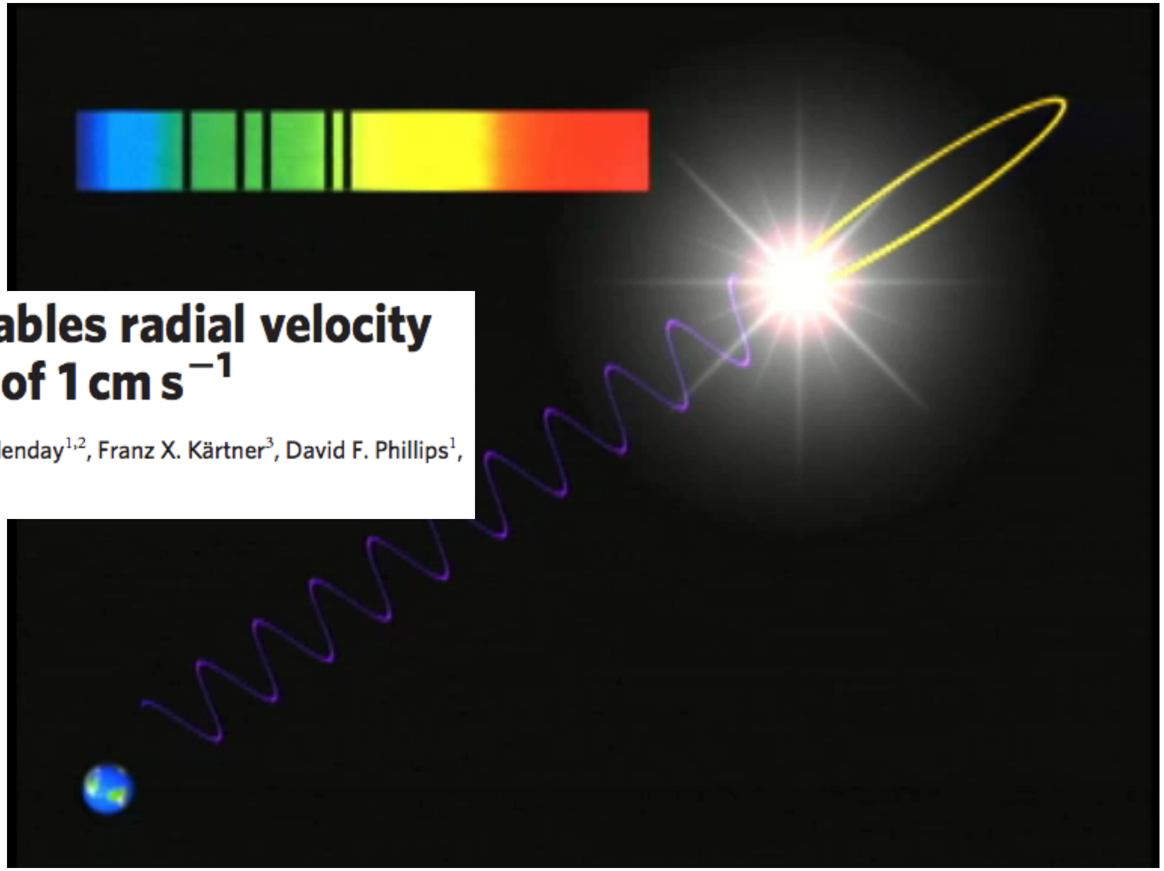


SMF input slit

Chris' latest microspectrograph

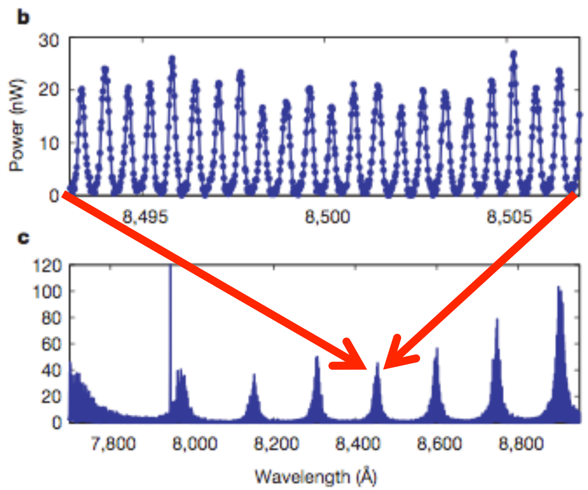


Hunting for extrasolar planets

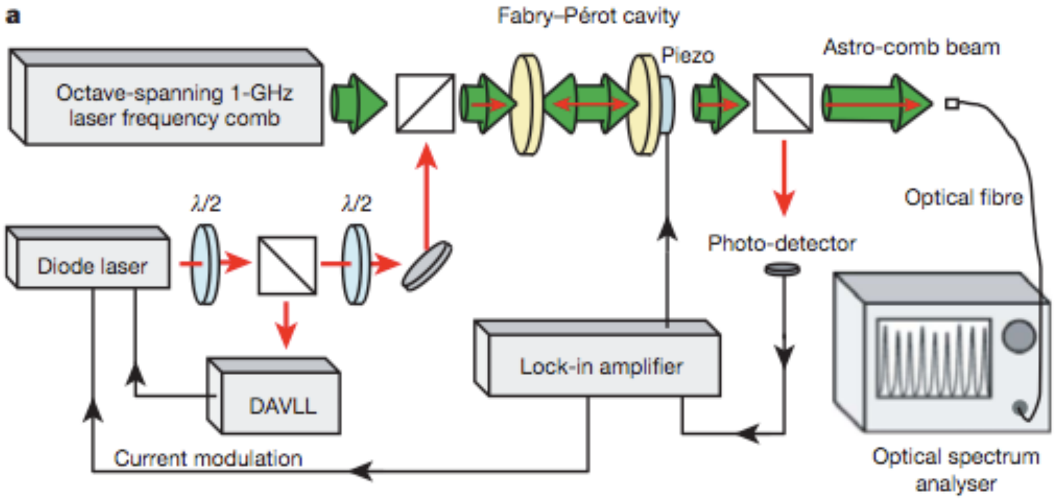


A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}

Chih-Hao Li[1,2], Andrew J. Benedick[3], Peter Fendel[3,4], Alexander G. Glenday[1,2], Franz X. Kärtner[3], David F. Phillips[1], Dimitar Sasselov[1], Andrew Szentgyorgyi[1] & Ronald L. Walsworth[1,2]



But spatial stability must also be addressed. This should easier to achieve with a small instrument.



Future topics

- Filtering & noise suppression (e.g. Fibre Bragg gratings)
- Interferometry
- Asteroseismology
- Quantum astronomy
- Laser cosmology
- Space astronomy
- Planetary astronomy
- Astrobiology
- …