Application to micro-optics

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24.04.2025

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I.Présentation

Module :

Micro-Optics

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Résumé :

This course consists of a descriptive presentation of the main applications of optical microsystems classified both according to the optical properties involved and the areas of application envisaged.

Mots-clés :

Optical microsystems, Micro-optics, MOEMS, MEMS

Pré-requis :

Optics courses at Bachelor's and Master's level, 1st year

Objectif(s) pédagogique(s) :

Understand the main applications of optical microsystems to date. The applications will be presented and classified according to the characteristics involved in order to highlight the common properties exploited and the new optical functionalities enabled by these devices. The material and manufacturing aspects of microsystems will be more specifically developed.

Plan du cours :

- Introduction
- Application history
- Classification of optical microsystems
- Brief case studies
- Which materials for which applications?

Conception & production :

Le Mans Université

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II.Lesson

During the past decade and most particularly in the late 1990's, MOEMS✭ and Optical-MEMS✭ field experienced fast growth. The first applications relied strongly on MEMS✭ technologies. We can date their appearance: projection display systems, components for optical fiber communications (sources, switches, junctions, routers, etc.), optical sensors and imagery.

The optical functionality allowed by Microsystems goes from light emission, detection and amplification, to switching, spatial modulation, routing and optical signal basic treatment. Optical Microsystems performance increased with the advances in the material field and the development of a system approach for their conception.

The high market demand for these objects, although unstable, coupled with the intellectual challenges led to a spread in research and development activities as much on the academic level as on the industrial one. In line with those efforts, governments and private investors provided the needed financing for those developments, making the emergence of new concepts and new systems possible. The first models have been on the market for many years, most particularly in the field of the projection display systems.

Miniaturization is one of the aspects of the use of optical Microsystems. From the point of view of material bulk and costs, it's a significant factor in many cases. However, in most cases, miniaturization alone can't ensure the commercial success of Optical Microsystems. Optical Microsystems conclusive success factors are due to the new optical functions, made possible thanks to the use of these technologies. There are three factors of Optical Microsystems fundamental success:

- the possibility to set up micro-device matrices at a large scale;
- the ability to reset optical properties, spatially and temporally, using located micro-actuation and micro-deformation.
- the nanoscale control of positioning precision and alignments for micronic scale devices, also known as “nanopositioning”.

This lesson is the continuation of the “Introduction to micro-optics” lesson, in which the basic concepts and the main manufacturing technologies are introduced. The goal is now to list a certain number of optical Microsystems applications, attempting to stress the emergence of these new functionalities and their impact on optical products.

The second part deals with an optical Microsystems' history, from research on the 1970's and 1980's solid-state physics to the current application.

The third part deals with a classification of optical Microsystems.

You will see in the fourth part some details about some specific Microsystems cases, with particular emphasis on the three factors mentioned above.

The last part is dedicated to a discussion about the problems relative to the materials needed in the drafting of these structures and about the challenges to be taken up, from a technical standpoint.

1. Applications' history

1.1. Some landmarks

a) The first display of a miniature torsion-mirror (~2x2mm)

It was carried out by Kurt Peterson at IBM in 1982.

If we take this innovation as a reference, Peterson anticipated that “silicon mechanical Microsystems could find a practical application for display screens (most particularly if we managed to integrate the silicon command circuit on the same chip by sending electronically on a matrix way the two-dimensional mirror network)”. This assertion turned out to be excellent judging by the success of Microsystems to make screens such as the Texas Instrument DMD (Digital Micro-mirror Device).

Rappel

See casework in Introduction to micro-optics.

We can quickly see that the screens using micro-mirrors gratings are the oldest scope of optical Microsystems. But we will see that the trend led to many other applications for micro-mirror networks.

The basic idea of digital micro-mirror systems consists in making a bistable micro-mirrors grating in order to intercept a beam of light so that one of the positions of a micro-mirror directs light on a screen while another position directs it to an absorbent block. For this, each micro-mirror activates and modulates a different pixel. We can also establishing a gray scale while making a dithering on the mirror. Color screens can be reached by standard methods: color wheel (the most compact and cheapest, and therefore, the most usual) or triple-mirrors gratings for the three fundamental colors (red, green and blue) combined with dichroic optical mirrors and displaying on the same screen. We will go into the details in the fourth part.

b) An alternative concept of micro-mirror screens

This concept was suggested in 1994 by a team led by David M. Bloom, from Stanford University. The modulation method, in contrast with micro-mirrors, consisted in using light diffraction by miniature grating, one for each pixel on a screen. Its inventor called it “GLV Grating Light Valve”. More details about the GLV structure and micro-mechanics are in the fourth part. In most cases of GLV technology implementation, light is emitted through a Schlieren system that blocks diffraction at order zero and lets diffraction pass at ± 1 order. The result: when the grating is inactive, light is not transmitted on the screen whereas during the actuation of the grating, the corresponding pixel on the screen is lit up by the interference pattern constituted by -1 and $+1$ orders. The main difference between GLV and micro-mirror made screens is that the GLV actuators produce long ($\sim 0,5mm$) and thin (a few microns) beams, varying between two vertical positions and that can be actuated faster (a tenth of a MHz versus some kHz). For this, the GLV needs a 2D pixel matrix, but is implemented on a simple line that is read quickly in the vertical direction to produce the complete effect. For the same reason, the GLV line can have many more pixels than micro-mirror screens of the same generation with the linear dimension. But there is a problem: as light modulation is based on diffraction, its efficiency is reduced and needs high power laser sources to have enough shine. This can explain why GLV is only for high technology display markets, which can bear laser sources cost and bulk in return for an excellent resolution of thousands of pixels by dimension on a large projection display surface (for instance for a digital movie). On the other hand, micro-mirror screens were a success on the mass computer and video projector market in which XGA resolution is sufficient and price, bulk and weight are decisive factors.

Remarque

It's interesting to compare GLV✯ and DMD✯ technologies because we can see how overlapping between optical principles (reflection vs diffraction) on the one hand and mobile elements (revolving rectangular blades vs thin beams moving vertically) on the other hand can influence the other system extrinsic parameters(choice of light source, resolution, bulk, price) and completely change the result of micro-systems production.

Remarque

We can notice that Texas Instruments has considered (since 2004) that the laser printer market can be an alternative for its DMD products.

c) " Silicon micro-optical bench "

Nowadays, a natural extension of micro-mirrors is the instruments known as "**silicon micro-optical bench**" for which optical devices are miniaturized in a silicon chip, whereas with traditional optics, several cm^2 are necessary on an optical table. Many ingenious systems have been implemented to treat light at one small scale, among them automatic micro-mirrors (pop-up), diffraction micro-lenses (blades with a Fresnel zone). Such systems have a strong potential for a large number of applications in optical treatment of signals and to set up captors.

* *
*

In all cases, the main application which emerged from the research efforts deals with optical gratings because they were in the field for which the needs in miniaturization were the most urgent. First of all, the main concern was to reduce the size of the routers for DWDM✯ applications by a scale factor similar to that allowing to pass from the size of a refrigerator to the size of a mailbox. It was an important need, not only because such DWDM nodes should be integrated in urban distribution central spots but also because an exponential growth in the demand in terms of production capacity was expected.

2. Optical Microsystems classification

Walker and Nagel studied and listed the various micro-technologies for optical applications and proposed to classify them according to the type of micro-optics used and the optical functions set up such as: sources, detectors, free-space optics, waveguide optics, transmission optics, reflective, diffractive and interferential optics (see the chart below):

Principles	**Microsystems**
Reflective optics	Micro-mirrors matrices for screens Phase correction two-dimensions array transducers
Diffractive optics	Fresnel blades Tunable gratings
Free-space optics	2D optical switches 3D optical switches
Waveguide optics	Optical planar waveguide Optical fiber alignment
Interferometric optics	Tunable external cavity Fabry Perot laser
Detectors	Bolometers Micro-spectrometers
Transmission	Choppers and optical micro-switches
Adaptative optics	Deformable mirrors to correct errors
Sources	VCSEL External cavity lasers

Micro-mirrors are used to point an optical beam at an optical waveguide, in or out of an optical fiber, and to turn light. Many systems functioning in a reflective mode were directly set up on silicon, on metallic surfaces or in multilayer systems with different refractive indexes. For instance, VCSEL (Vertical Cavity Surface Emitting Laser) is a micro-system implemented from a multiple pileup of different index layers in order to obtain very high reflexion coefficients.

Micro-mirror matrix is the widest application of optical micro-systems and is mainly used for projection display systems and for free-space optical communication.

The diffractive optics makes it possible to make planar micro-lenses, Fresnel lenses and gratings.

In the systems we just talked about, the light spreads in free-space before reaching the actuator that deflects or diffracts it. Another alternative to control light: to confine it in an optical planar wavelength. It's then impossible to interact directly with it, however we can modify its spread by positioning an actuating micro-system near enough to the planar wavelength for a possible coupling by the evanescent wave. The coupling by evanescent wave results in a stage delay that can be used to make optical switching and so on.

Research in micro-systems highlighted many devices. Some of them became commercial successes, and some not yet. We noticed that miniaturization is not sufficient to create new markets or to become more competitive. The most successful optical micro-systems combine at least two or three factors we already mentioned: possibility to set up micro-device matrices, ability to reset optical properties and nanoscale control of precision of positioning.

2.1. Sources

Sources include:

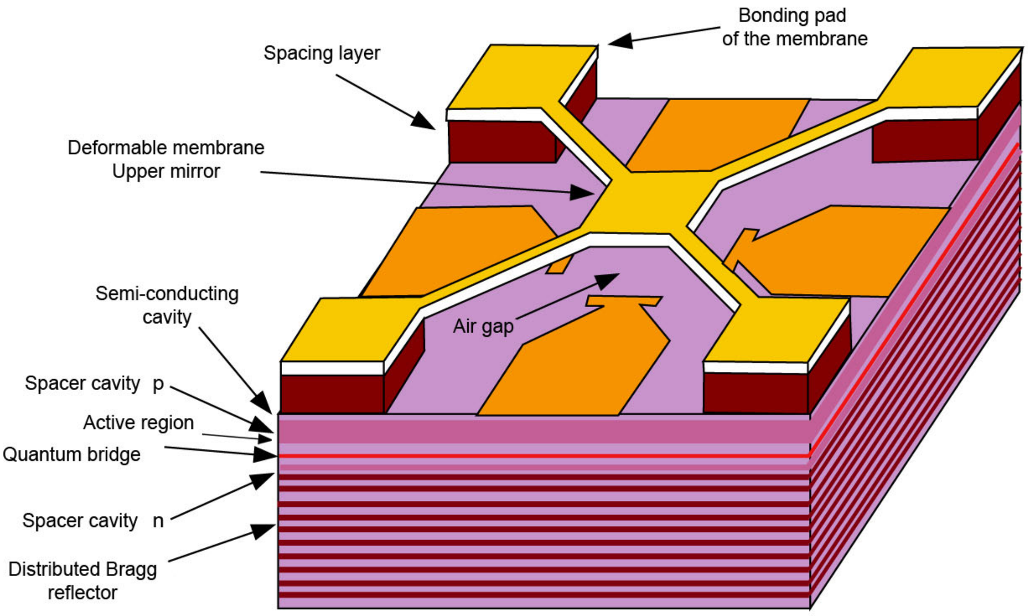
- thermal sources

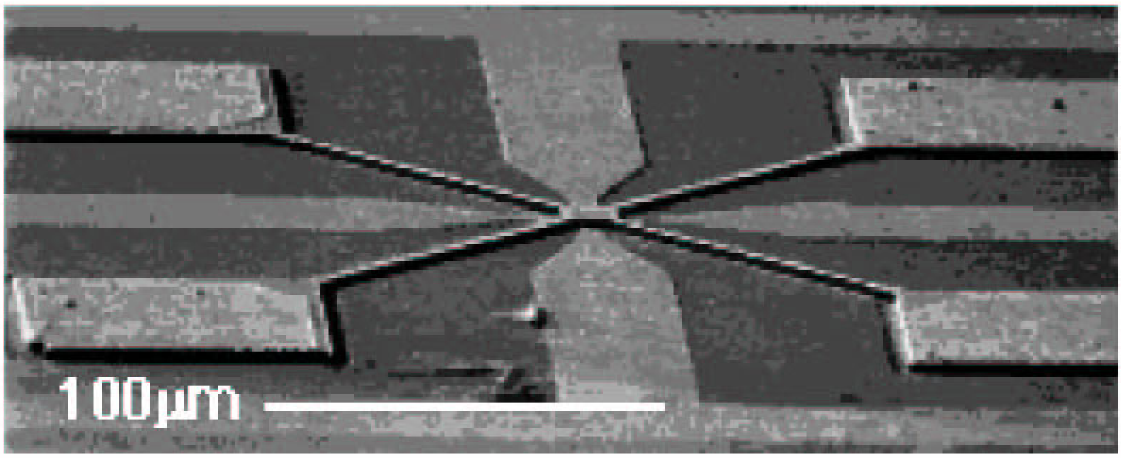
- semi-conductor devices:
    - LEDs
    - Vertical cavity surface emitting laser (VCEL)

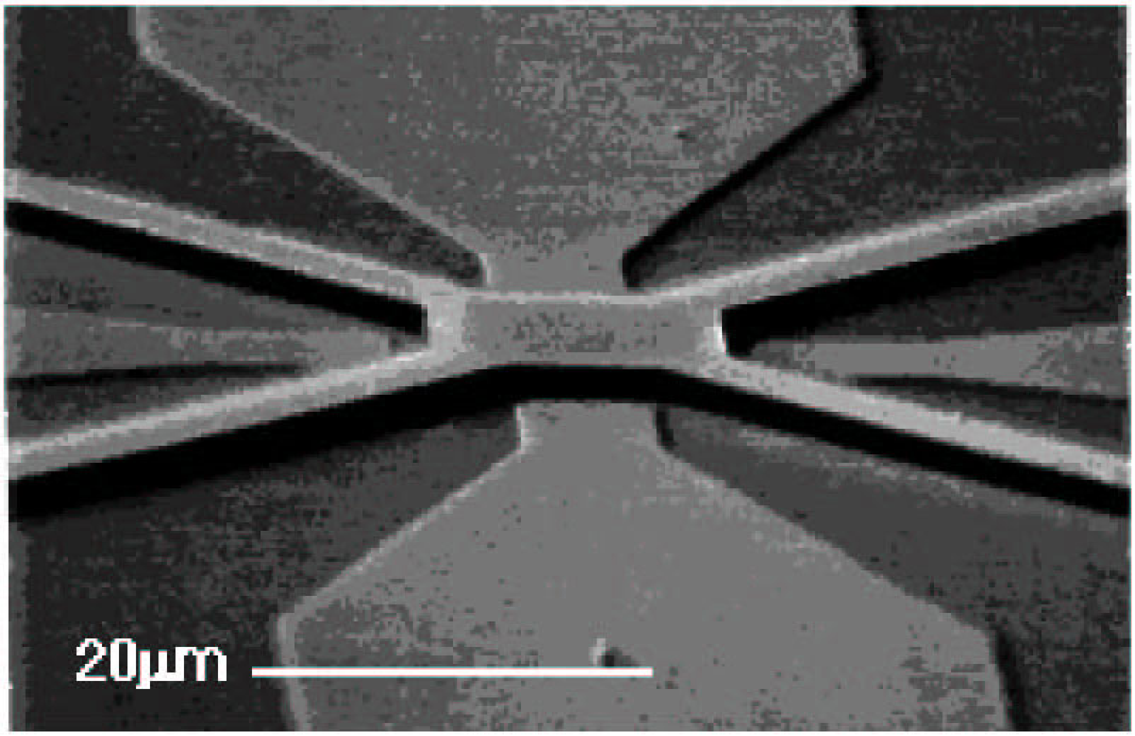
We can notice that these devices using Microsystems micro-fabrication technologies are not always considered Microsystems. But the integration resources prove that they are obviously part of more complex Microsystems.

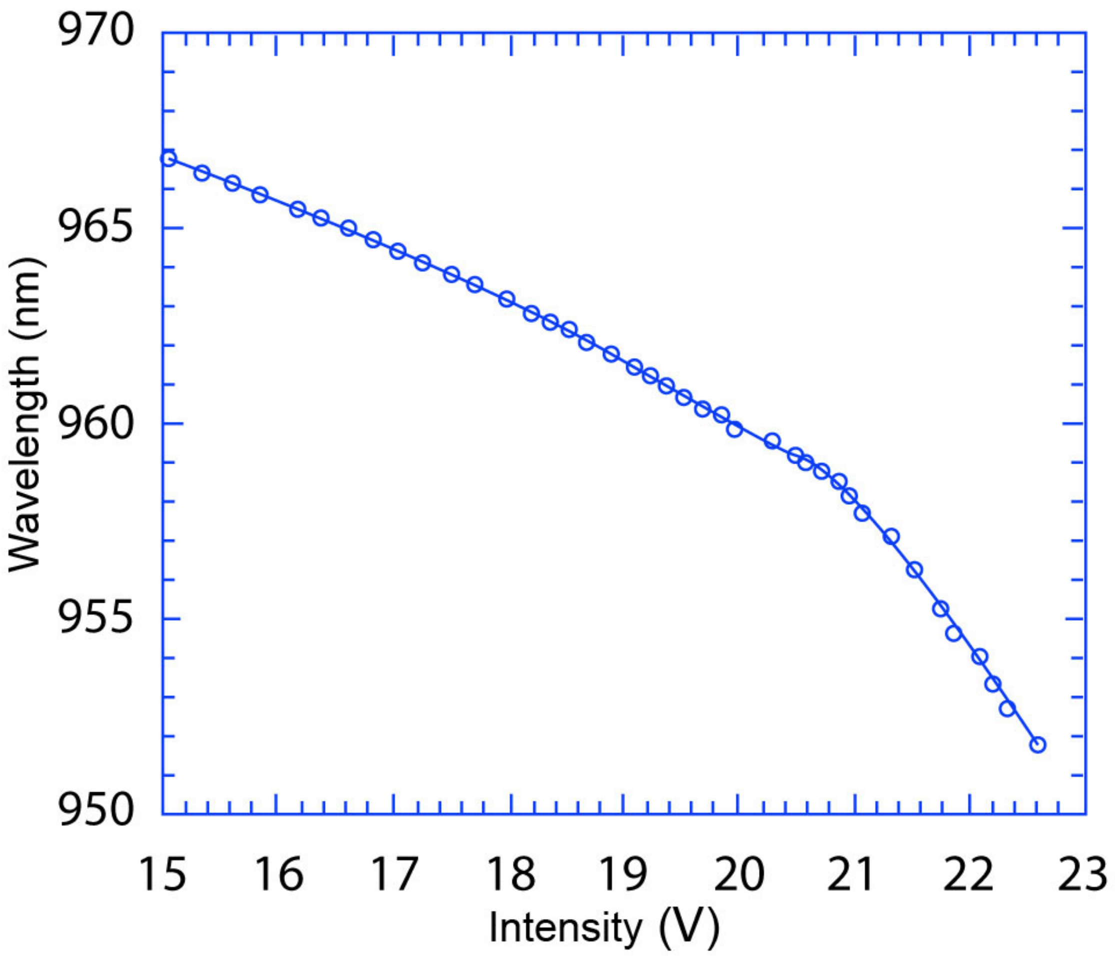
Exemple

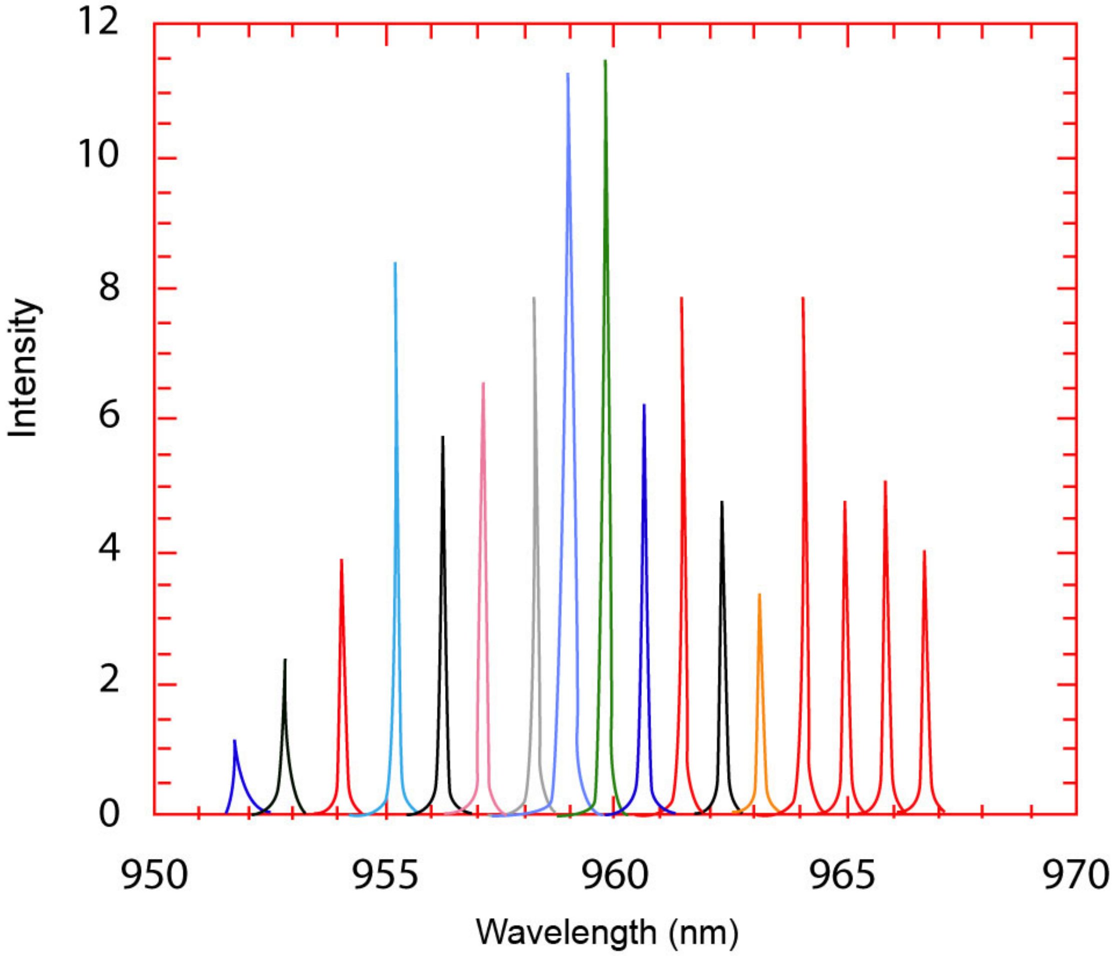
Example of VCEL✯:




100µm


20µm


970
965
960
955
950
Wavelength (nm)
15
16
17
18
19
20
21
22
23
Intensity (V)

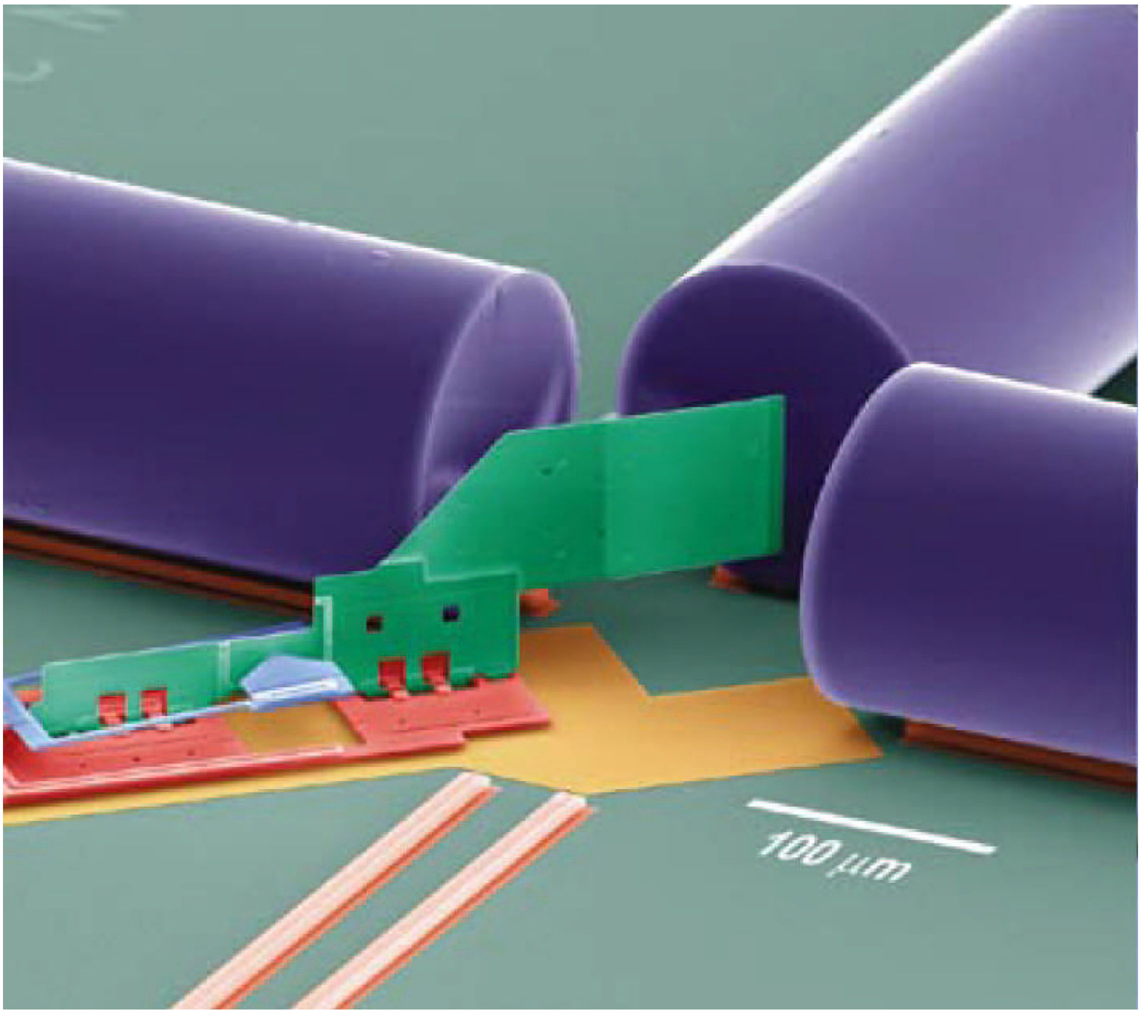


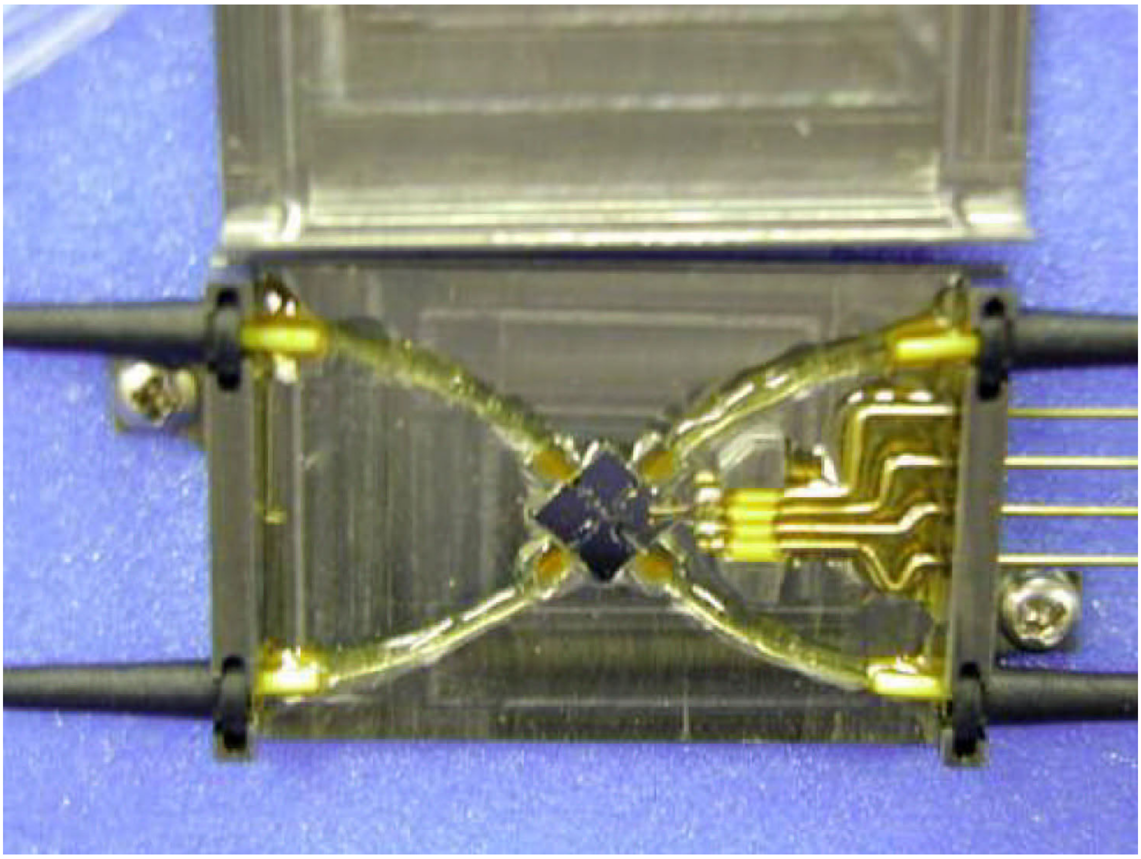
Those micro-lasers can be tunable by micro-displacements of the deformable mirror of the cavity output.

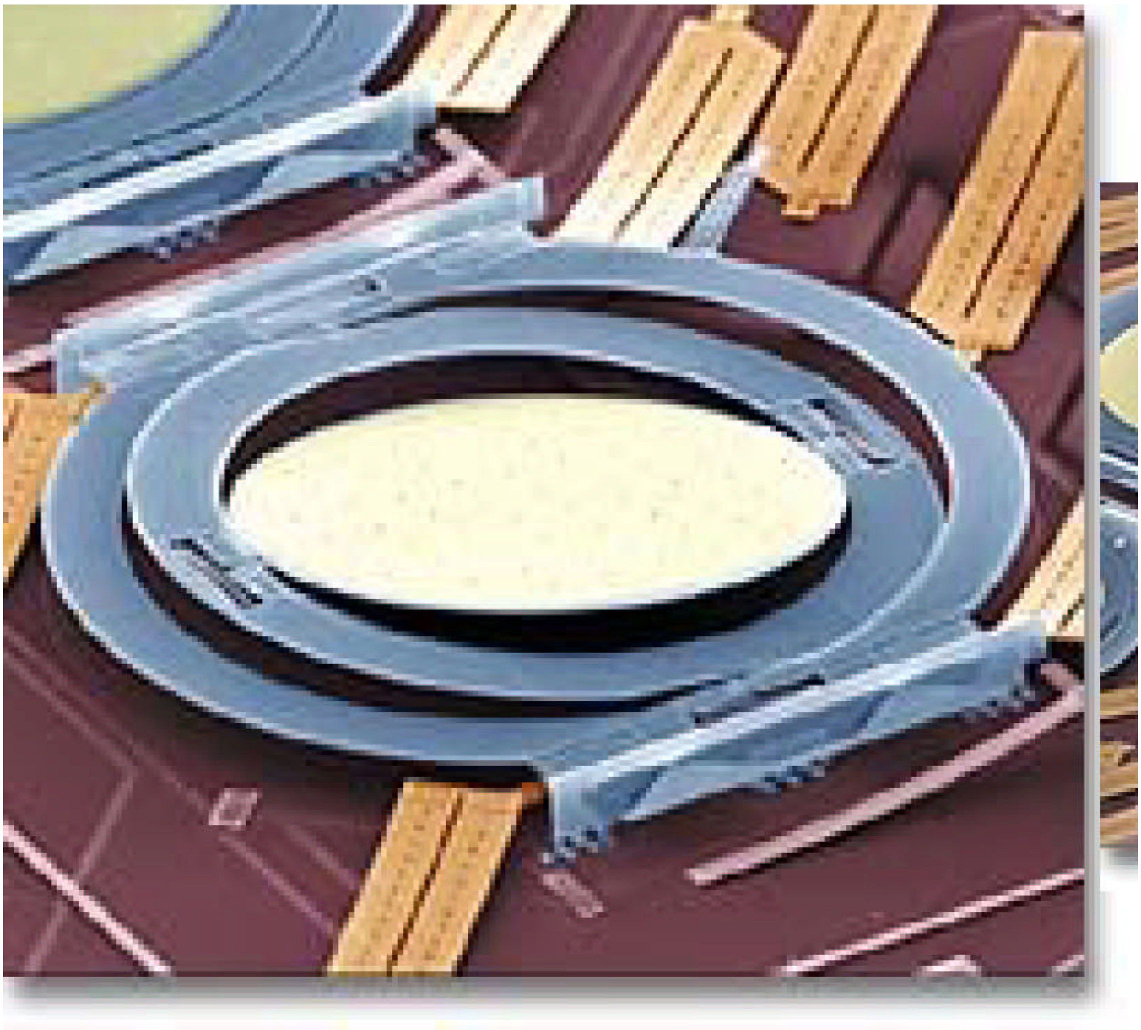
2.2. Optical guidance systems

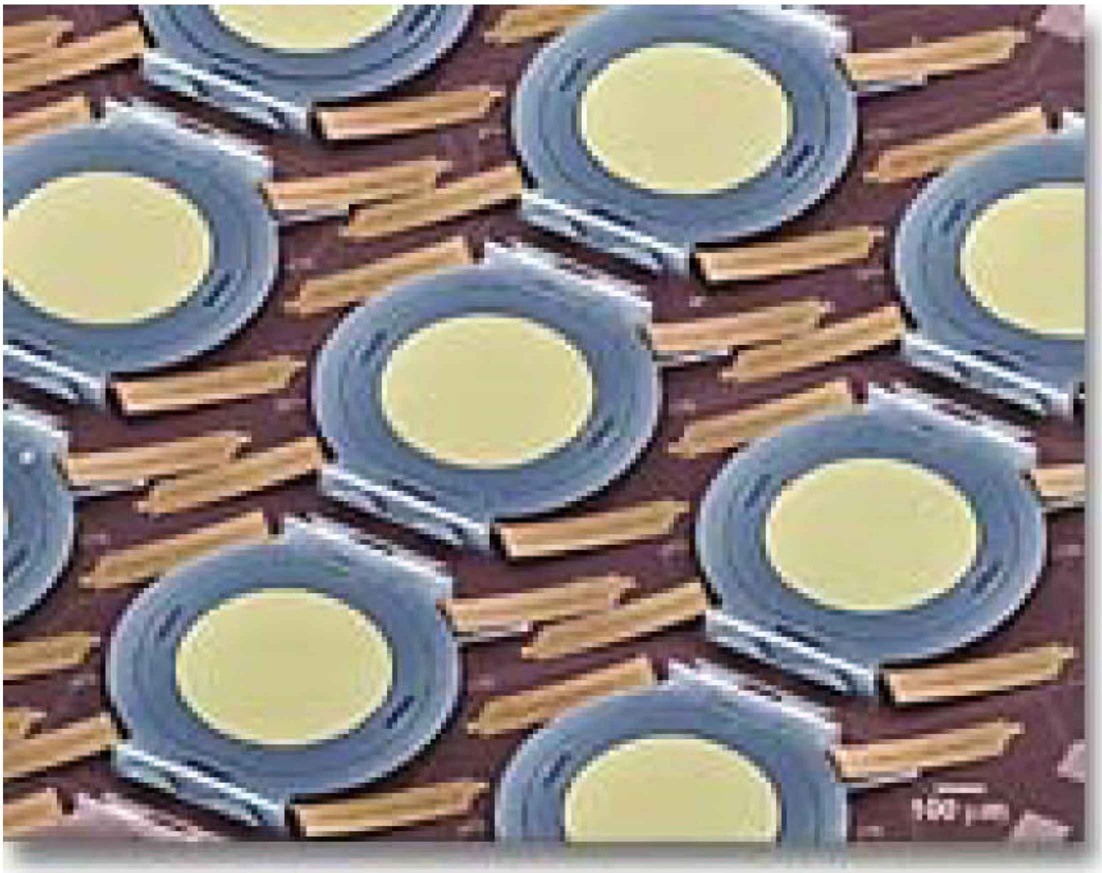
Are included:

- optical planar waveguides
- optical switches

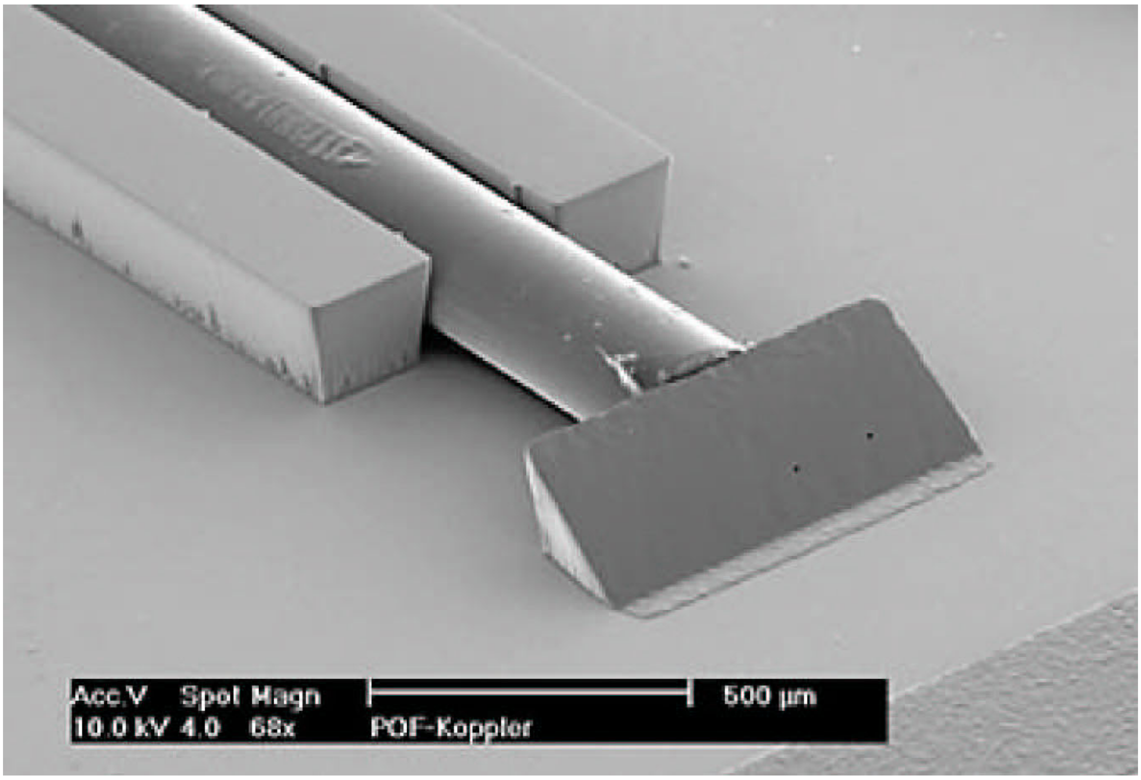

100 µm

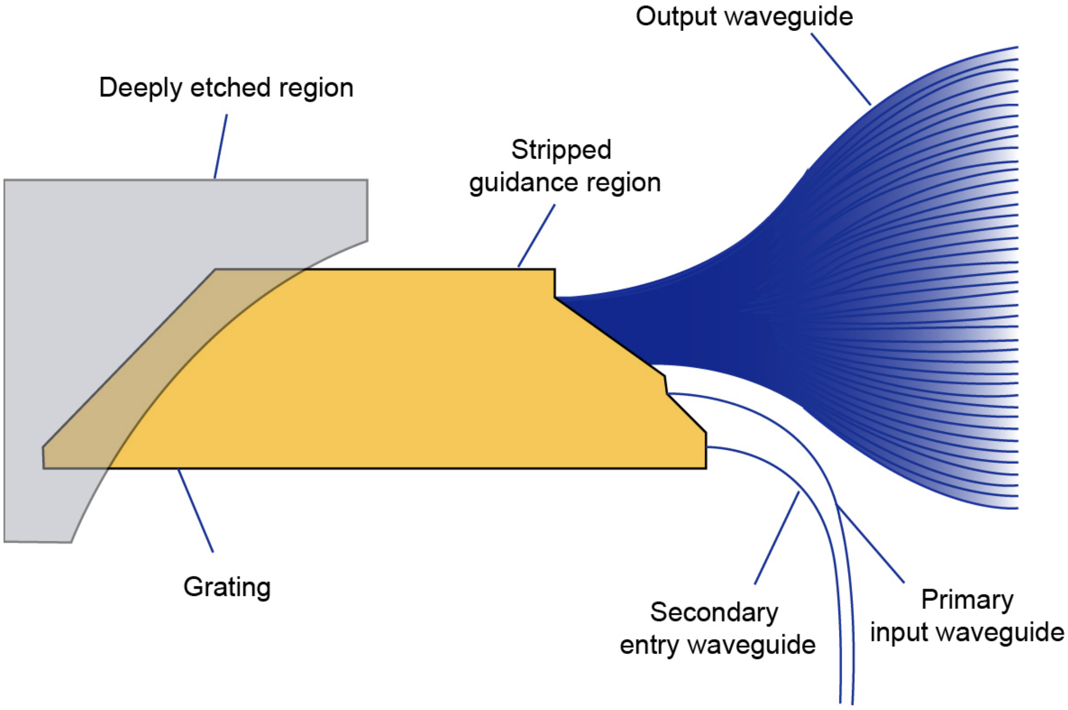




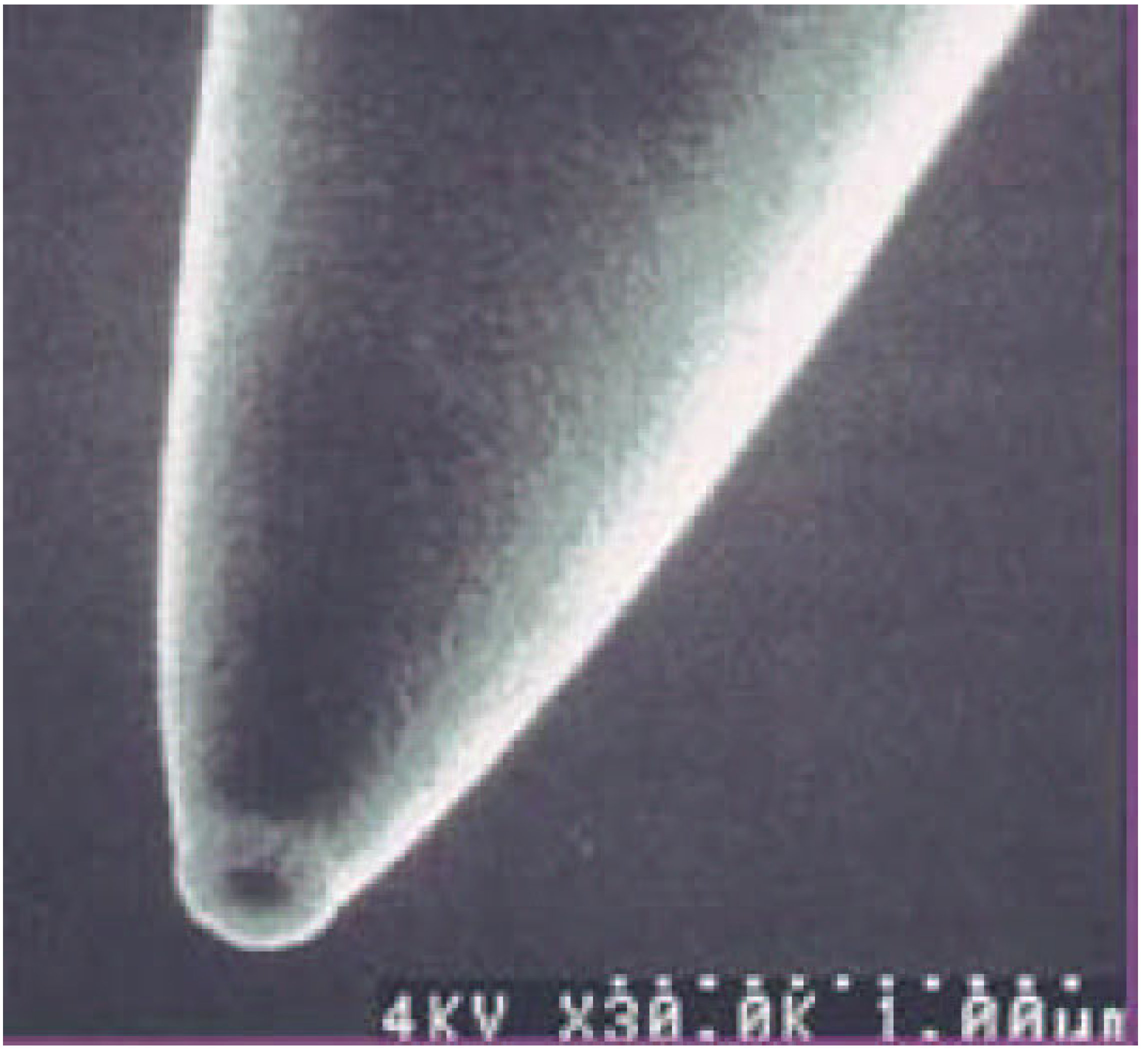


- optic mixers

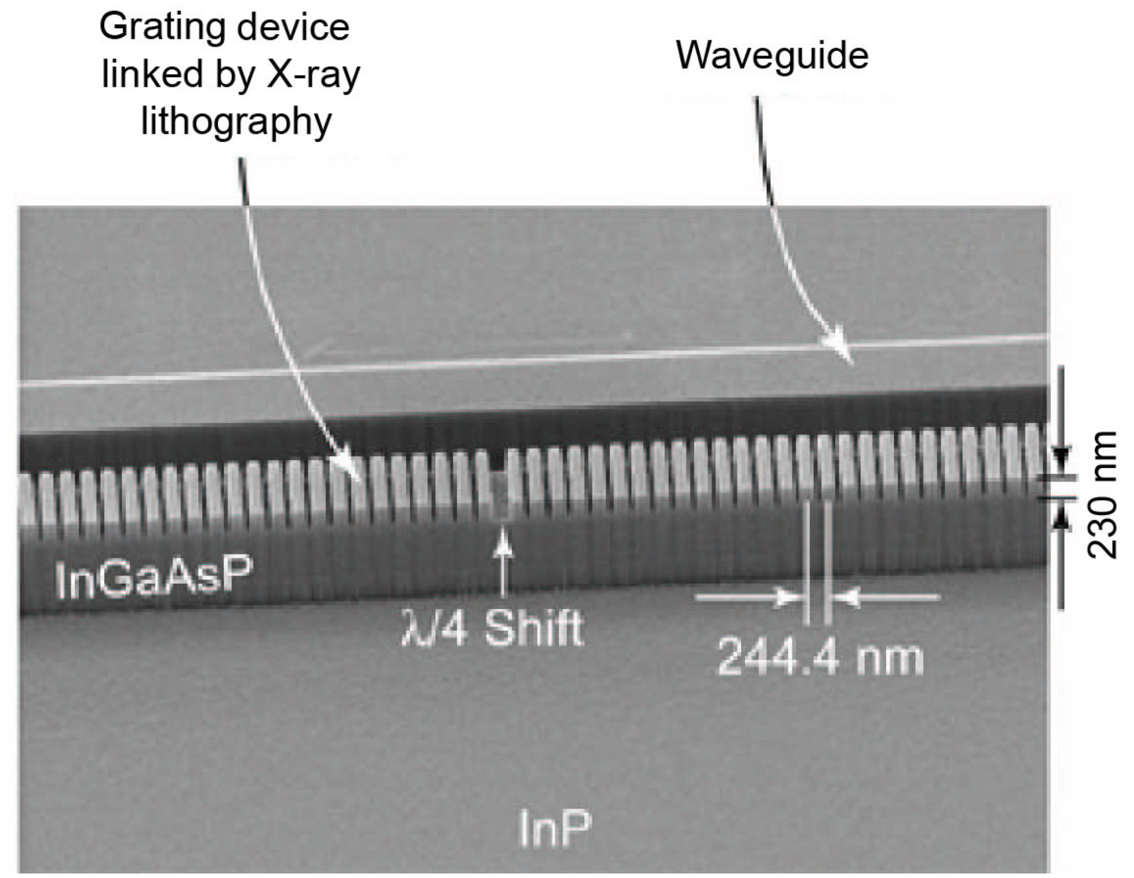


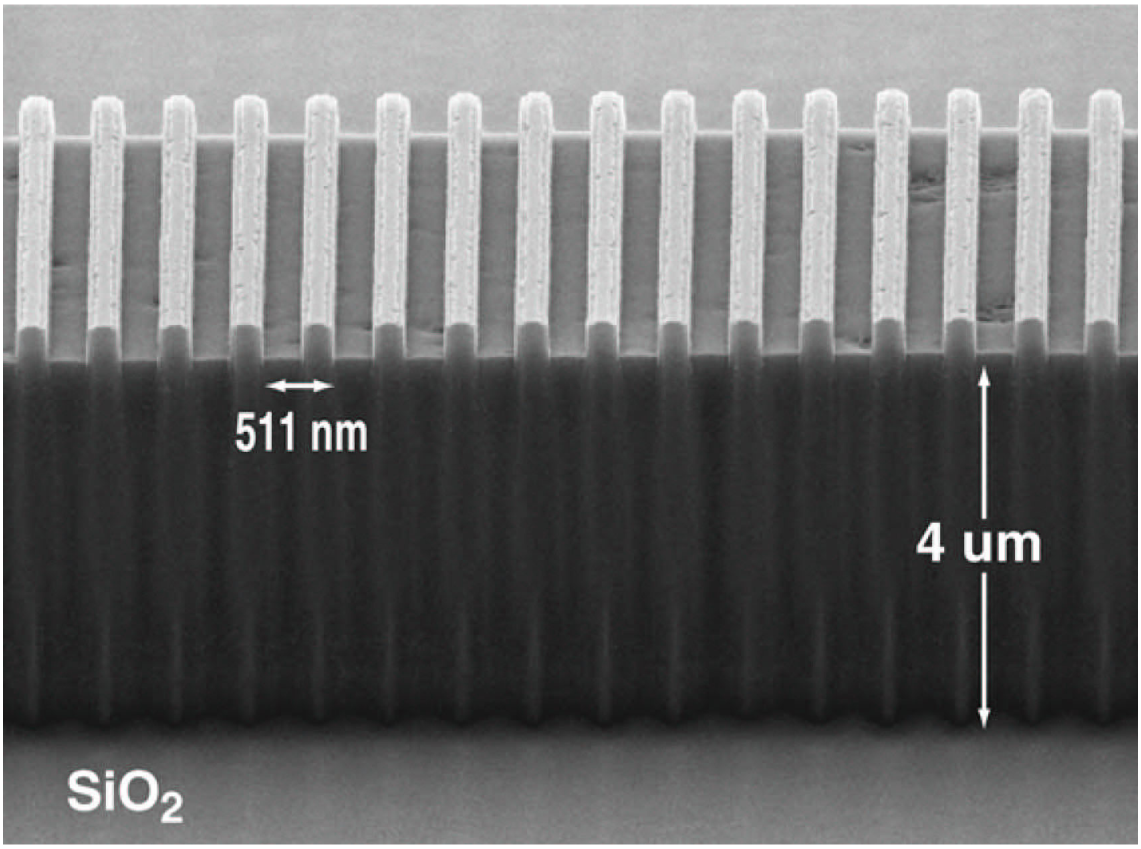


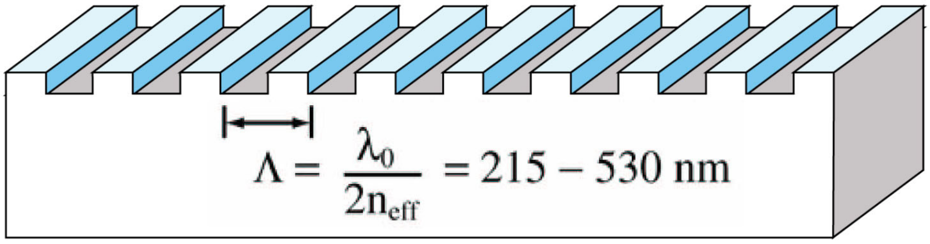
- clamps or optical fiber probes for captors or near field microscopy

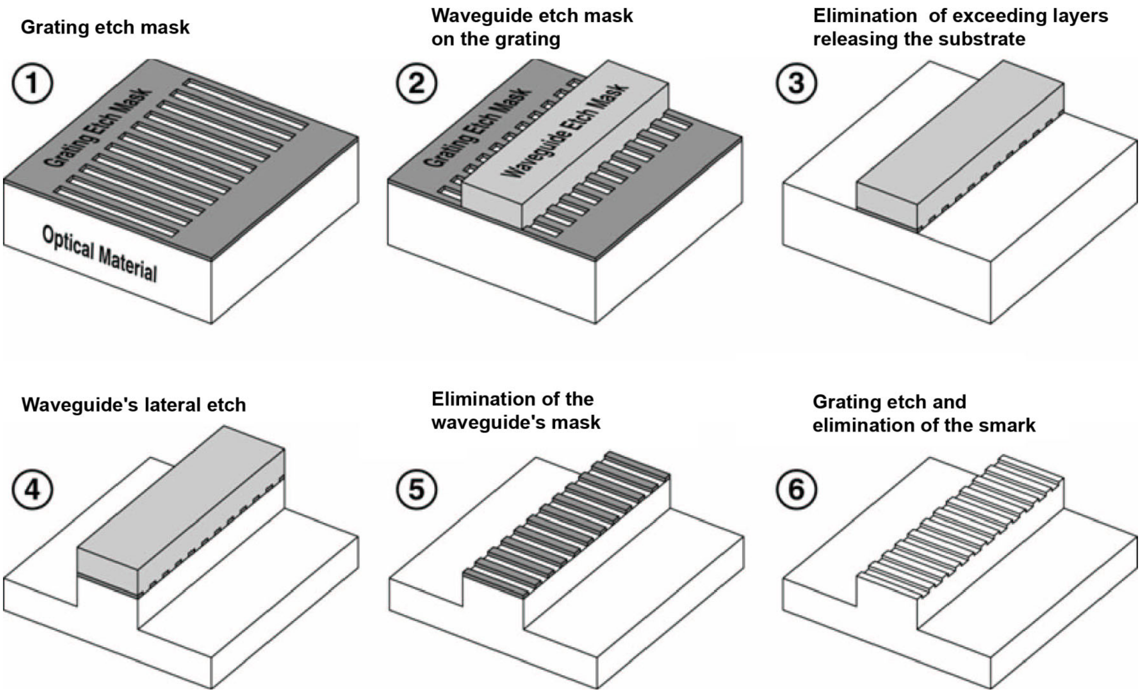


- integrated distributed Bragg reflectors

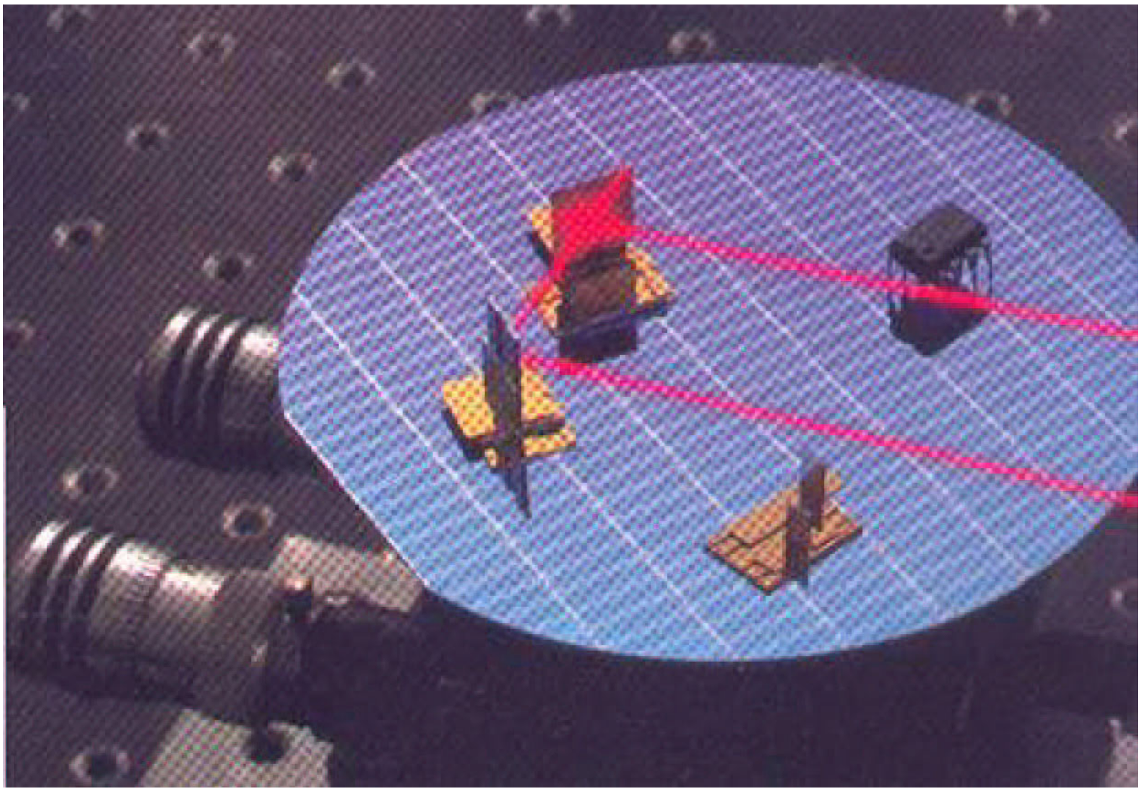

Grating device linked by X-ray lithography
Waveguide
230 nm
InGaAsP
λ/4 Shift
244.4 nm
InP

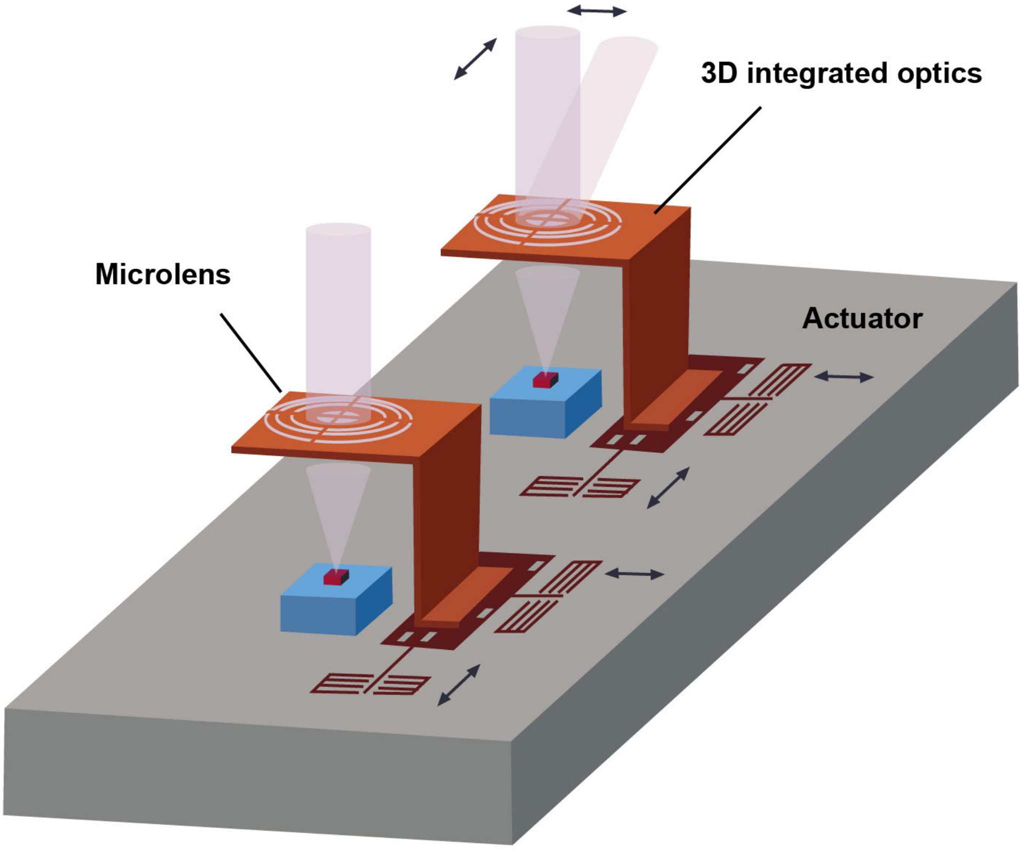

511 nm
4 um
SiO2


$\Lambda = \frac{\lambda_0}{2n_{eff}} = 215 - 530$ nm



- optical micro-benches

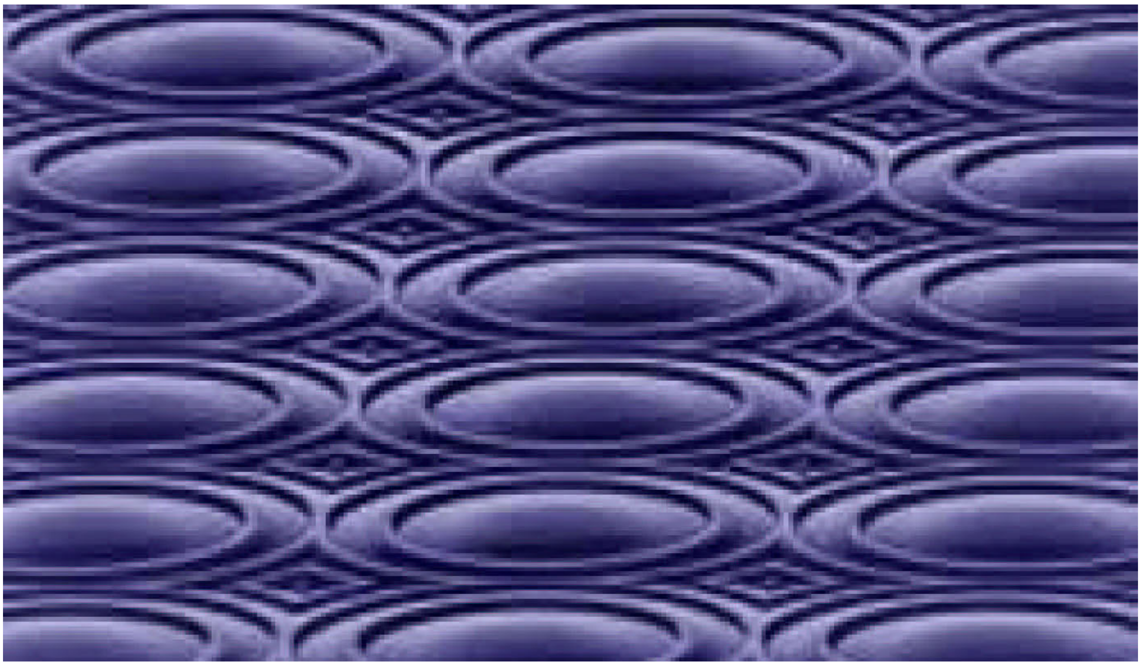


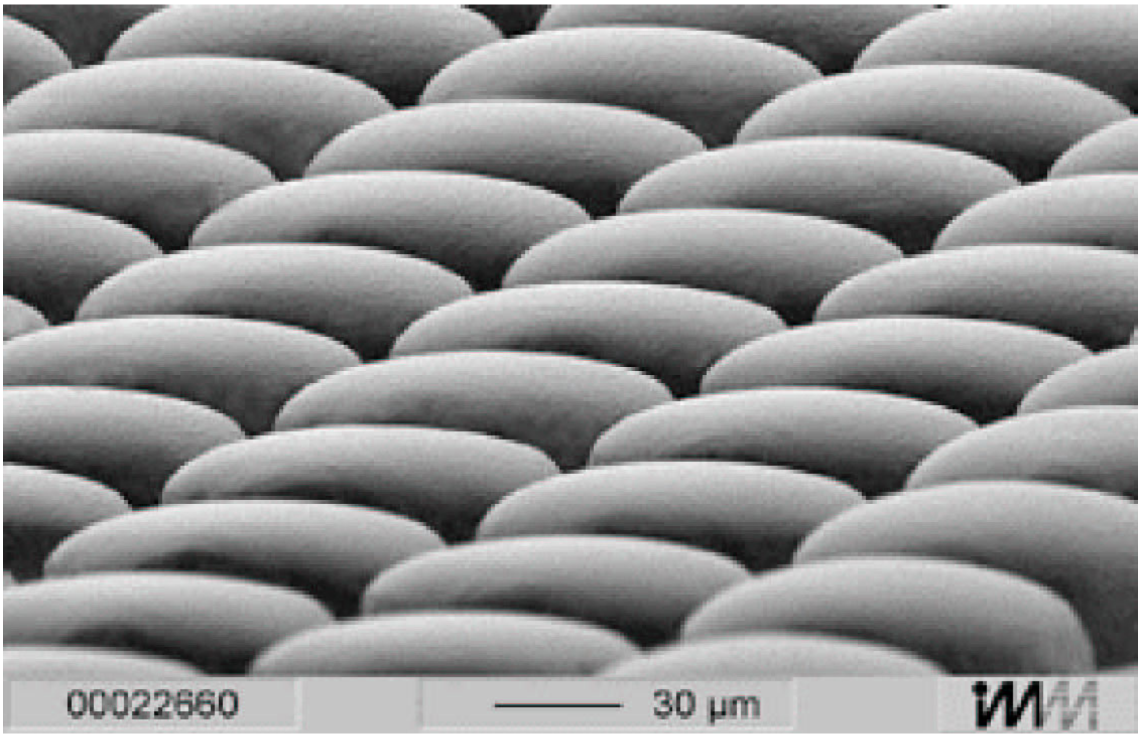


2.3. Transmission devices

Are included:

- refractive micro-lenses arrays

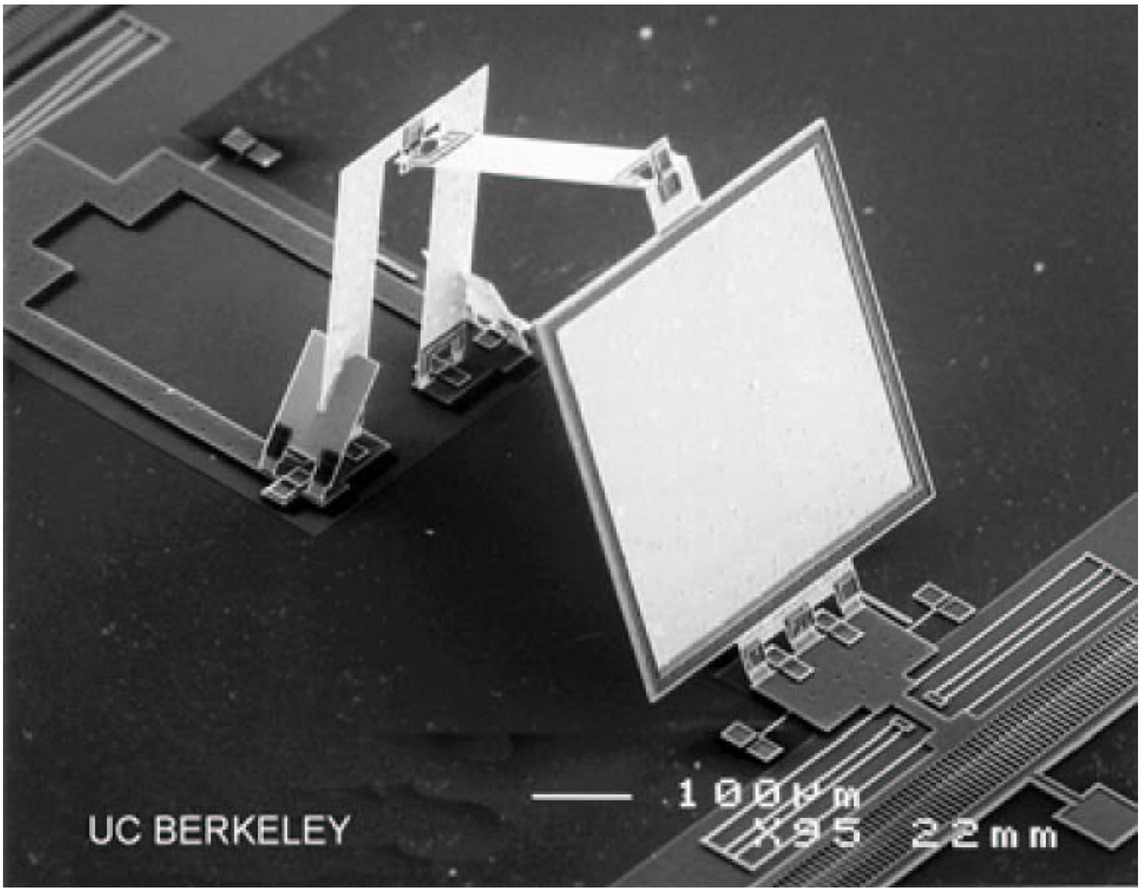


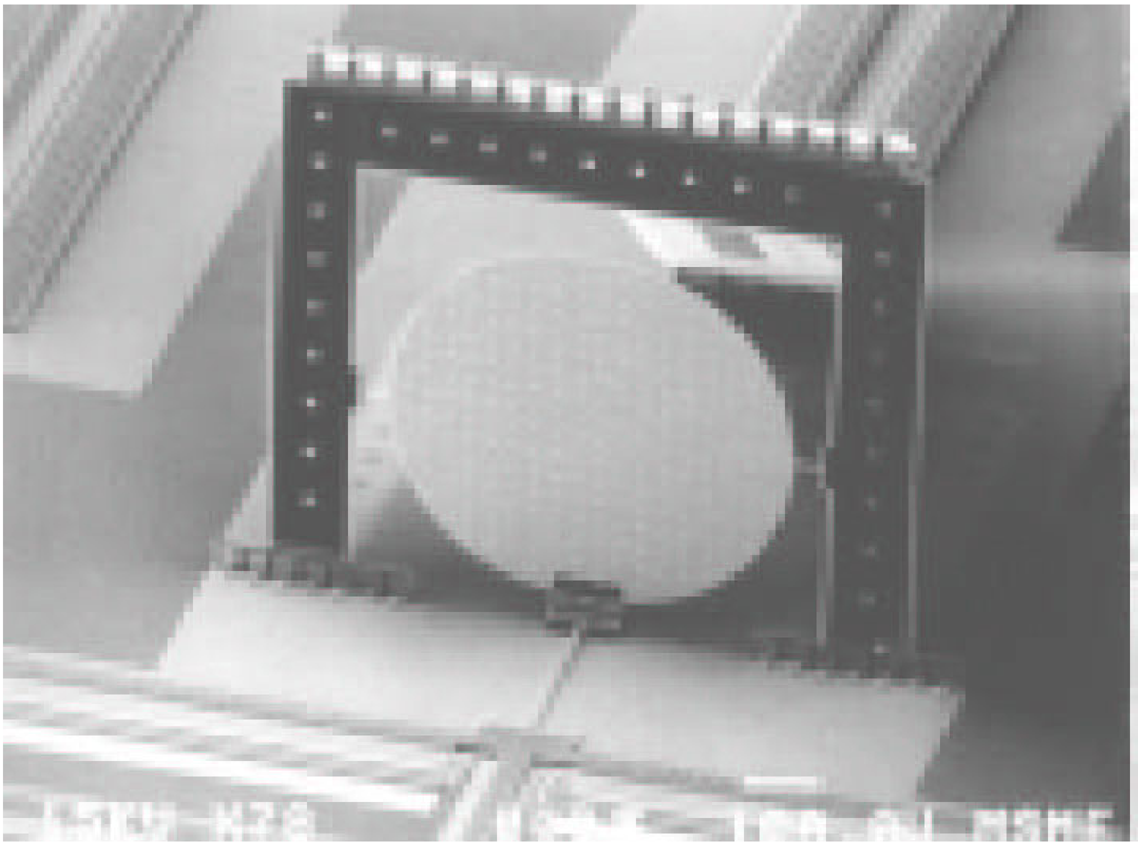


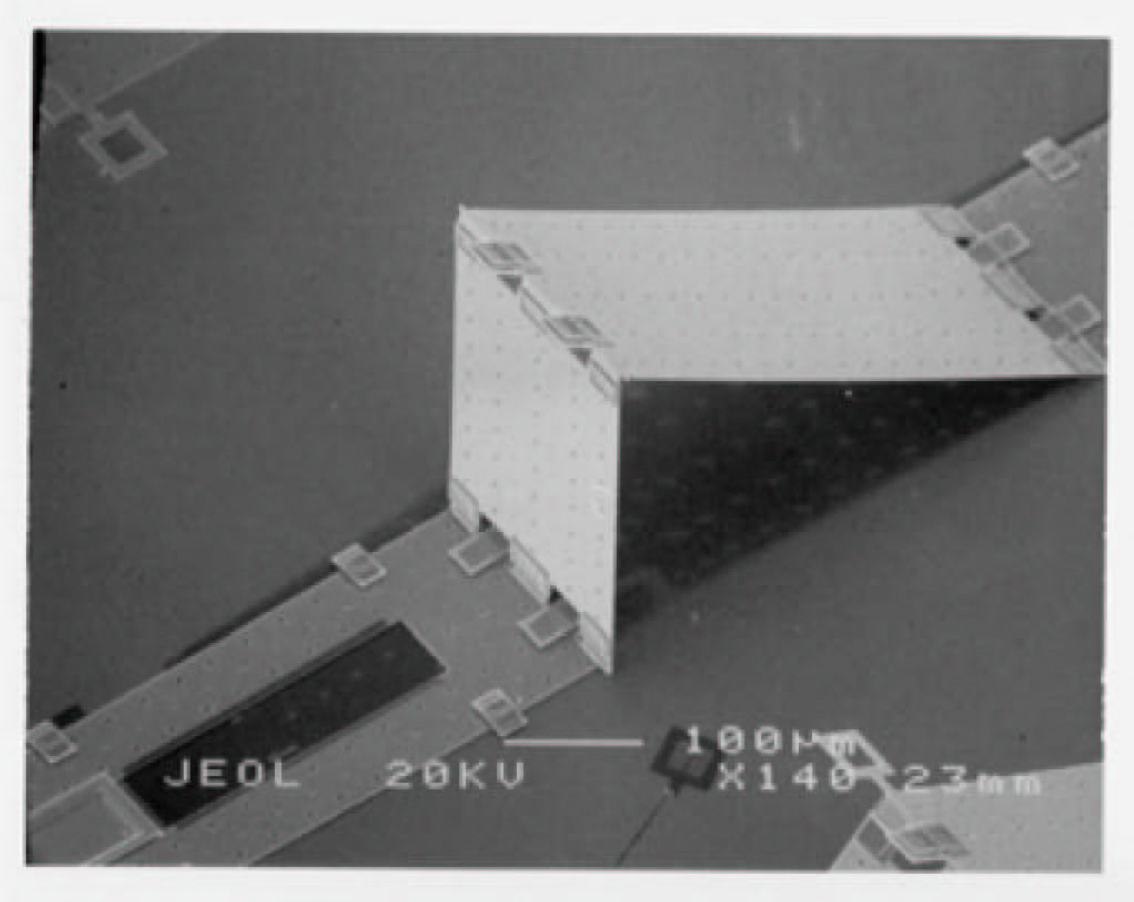
- filters
- beam splitters
- prisms
- quantum gates
- switches and choppers

2.4. Reflective optics

For those kind of applications, we use a thin metallic-or silicon-made reflecting layers or dielectric multilayer structures to make simple mirrors or mirror gratings to manufacture, for instance, adjustable micro-mirrors as DMD or tunable reflecting filters.



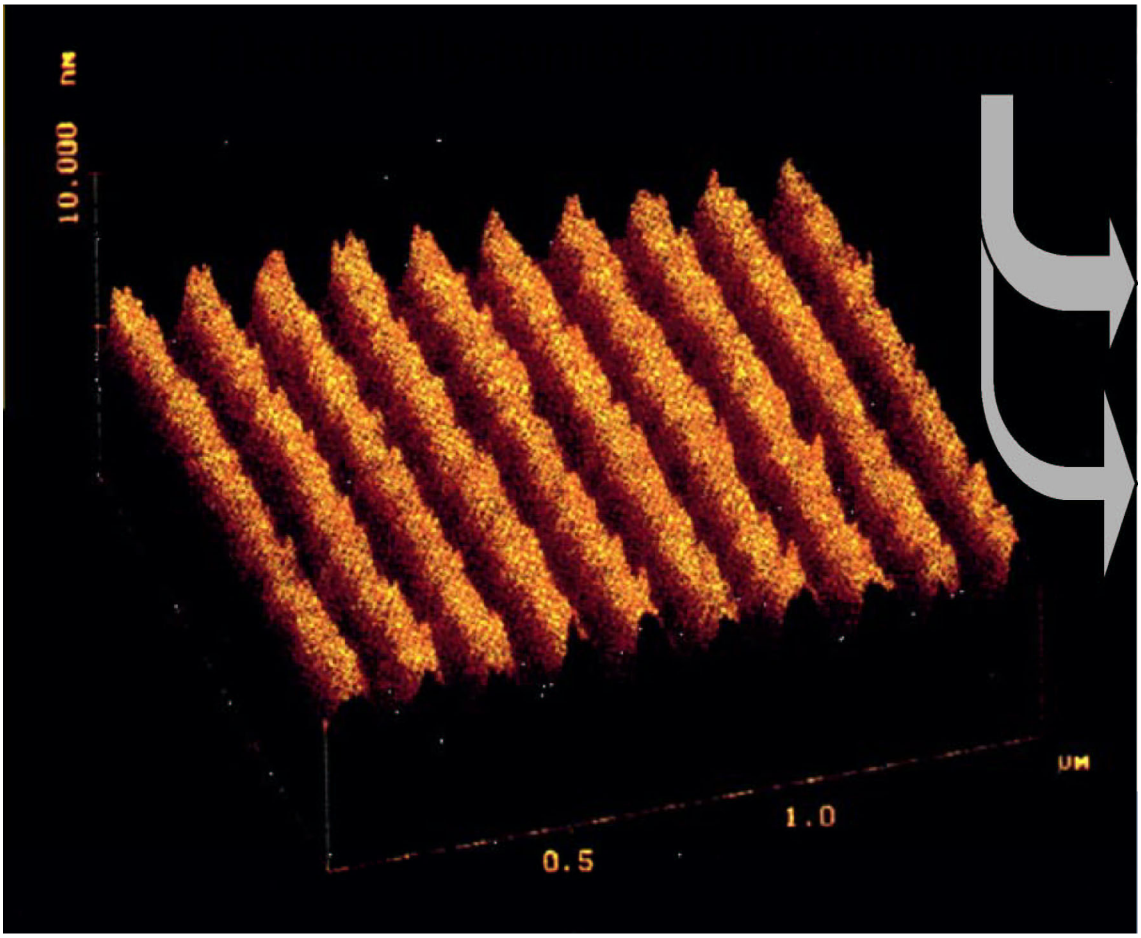


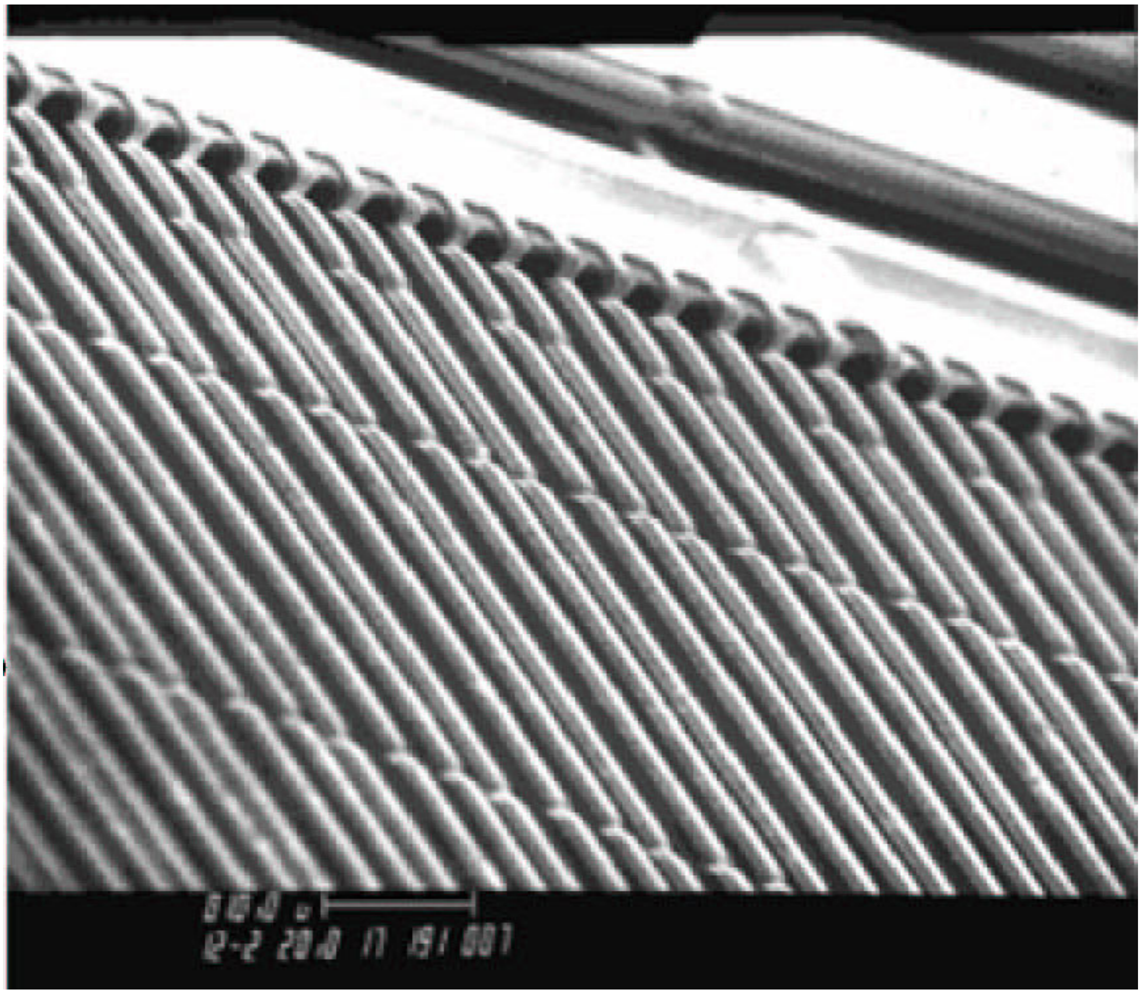


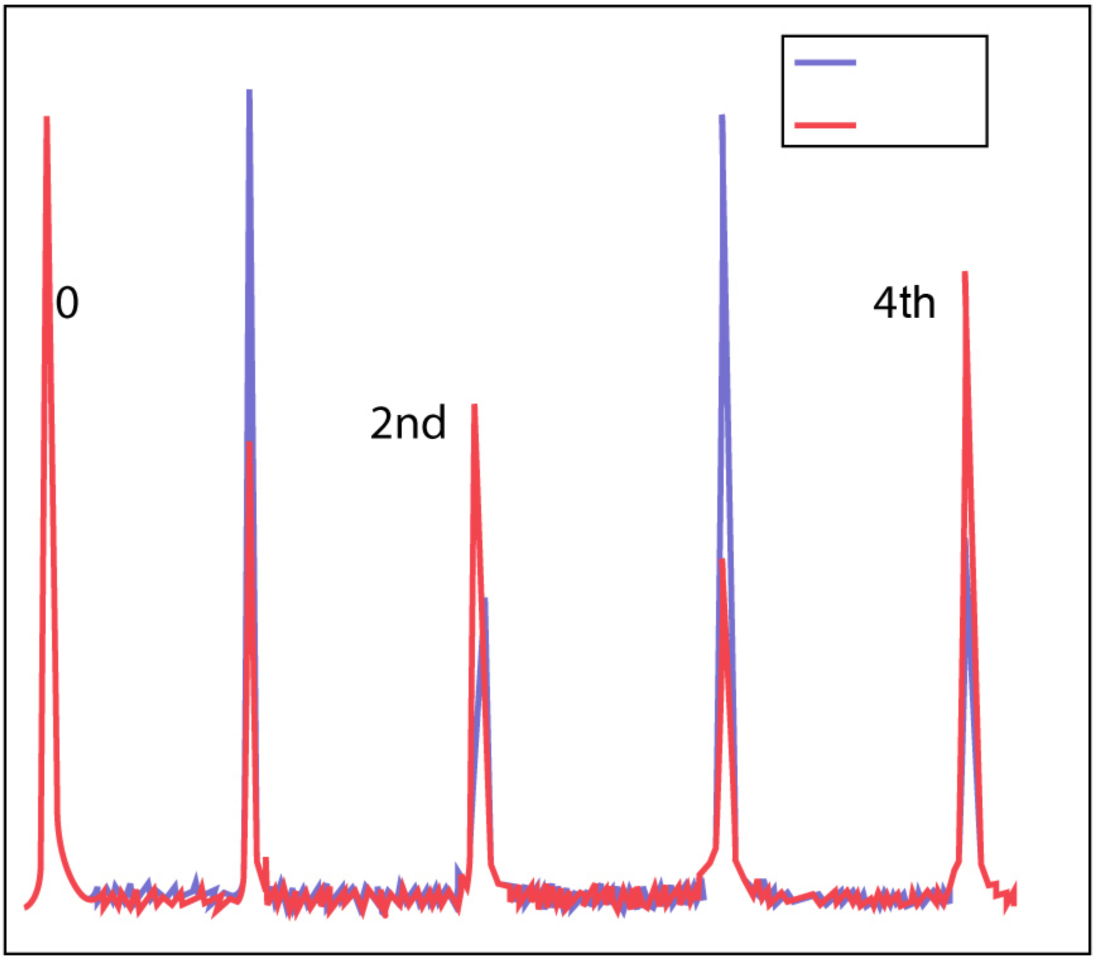
2.5. Diffractive optics

Diffractive optics enables to make:

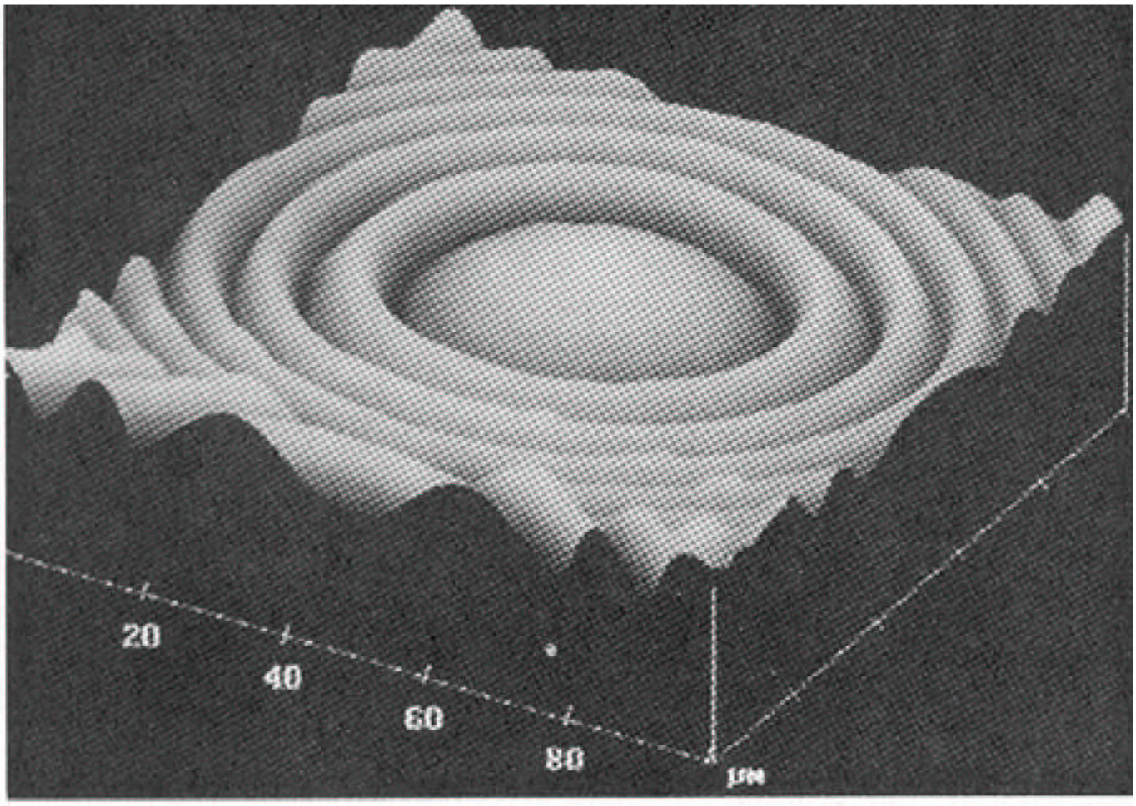
- diffraction gratings


10.000 nM
0.5
1.0
uM





- micro lenses



- Fresnel lenses

With different direct or indirect etching technologies, for example with electron beams or through a mask.

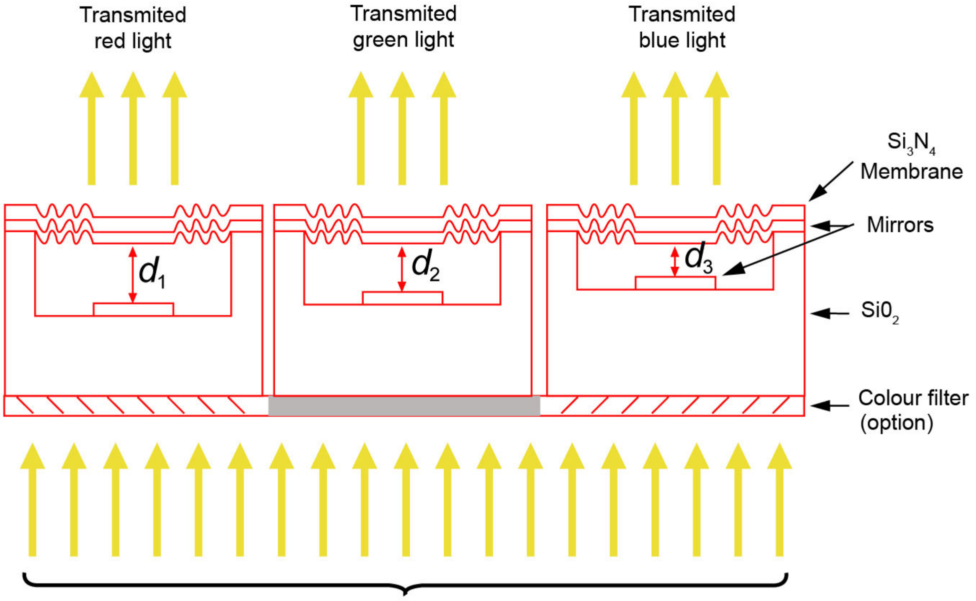
2.6. Interferential optics

Thanks to interferential optics, we can set up:

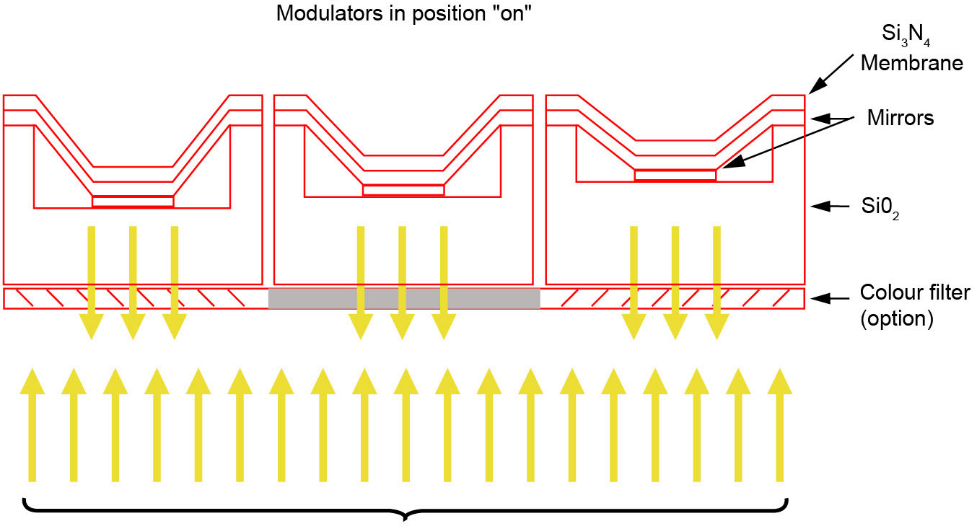
- Fabry-Pérot interferometers
- Mach-Zehnder interferometers
- Michelson interferometers

Which contain optical Microsystems.

Fabry-Pérot interferometers are made of membrane multilayer structures in which the mechanical or electromagnetic actuation of the suspended membrane movement enables modifying the length of a light optical path in order to change the length spectrum array of the light transmitted.

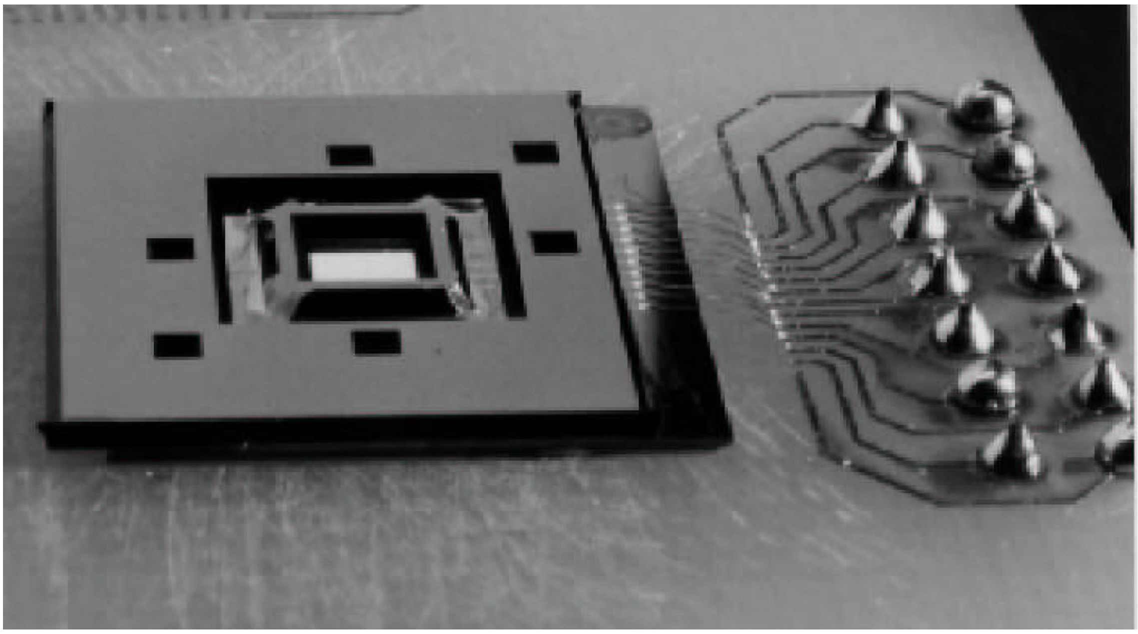


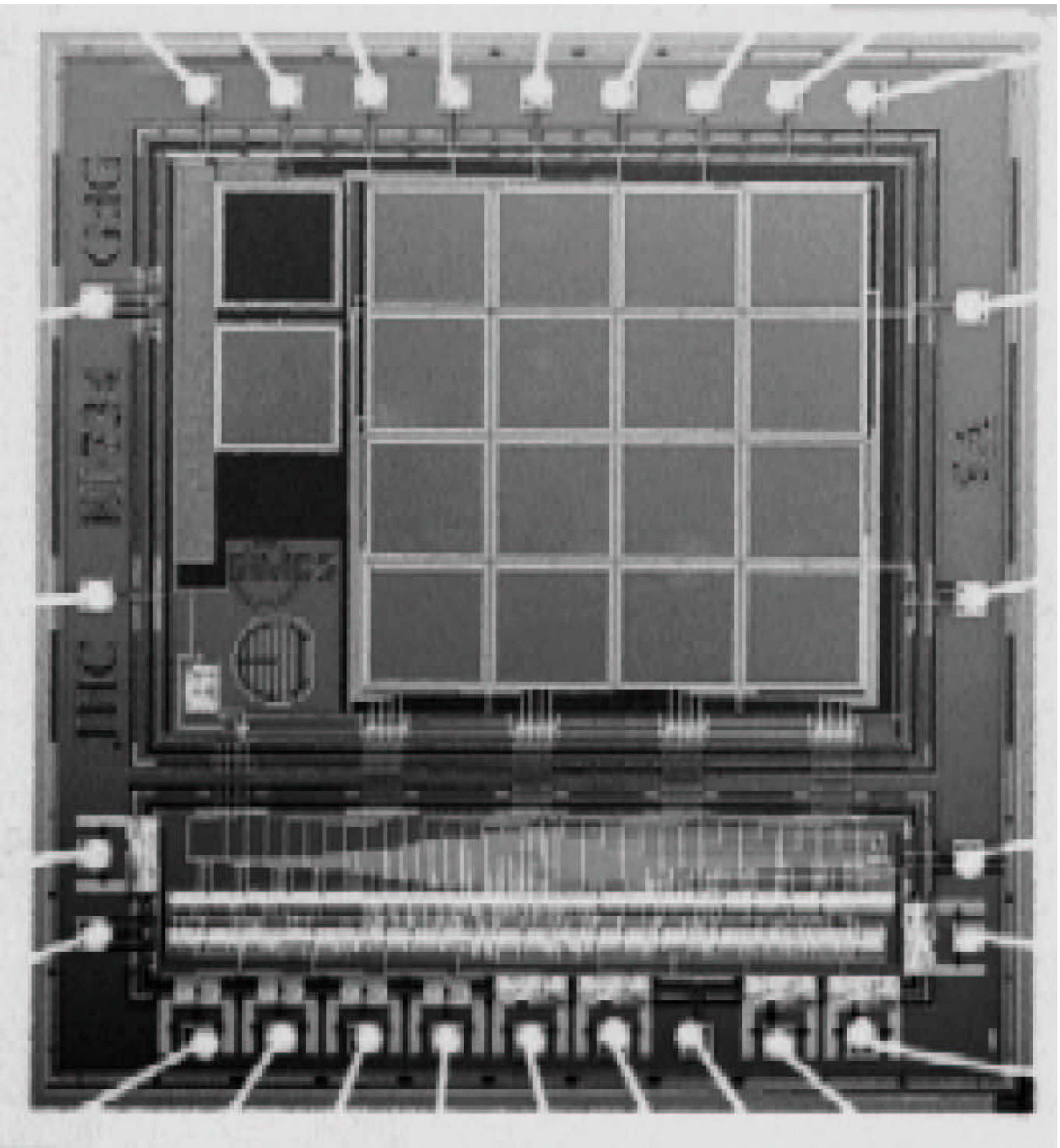
White light in normal incidence
Modulators in position "on"



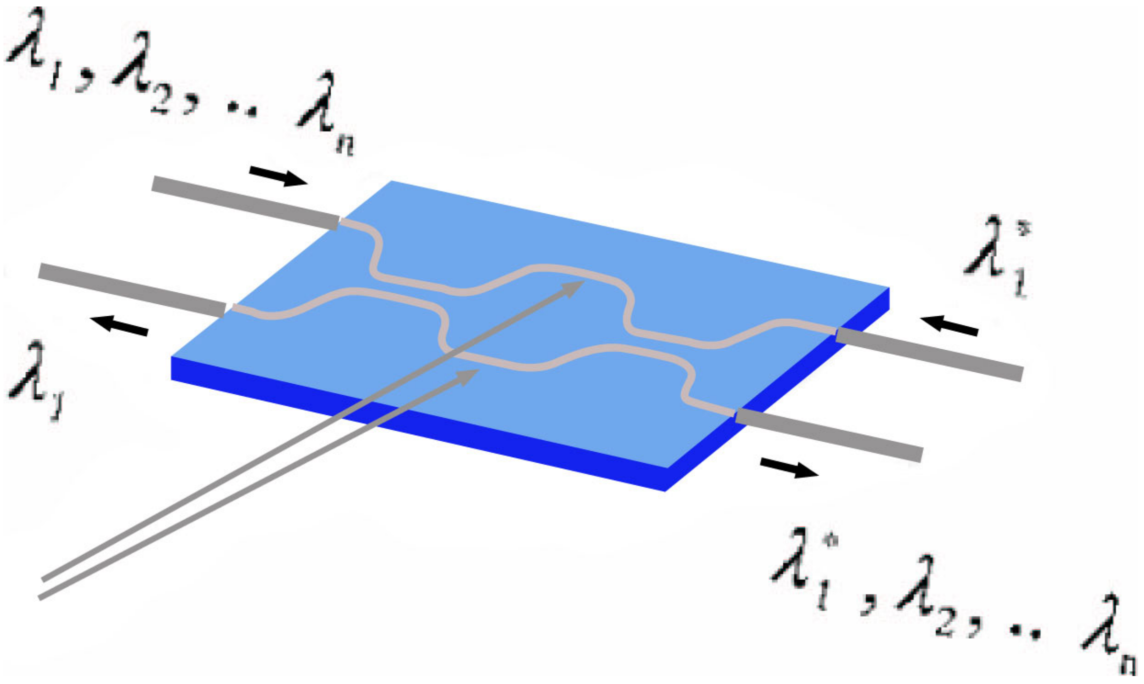
White light in normal incidence
Modulators in position "off"

We can also make arrays of Fabry-Pérot interferometers, in particular to cover wider spectral regions.





The other types of interferometers can be set up in integrated optics and use directional couplers, of which disruptions brought to the various arms make it possible to change the incoming wave phase states in the coupler so the output interference pattern evolves.



2.7. Detectors

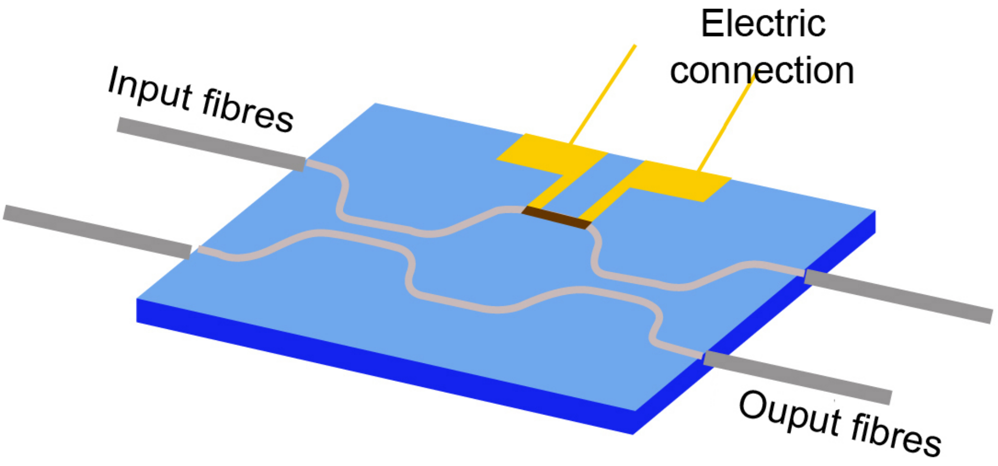
Are included:

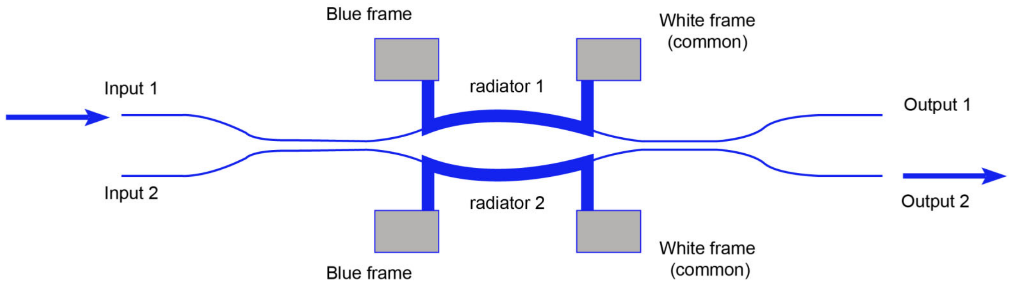
- Photodiodes, integrable to more complex Microsystems
- Micro-bolometers using electrical micro resistance in order to measure light intensity flows

2.8. Main applications

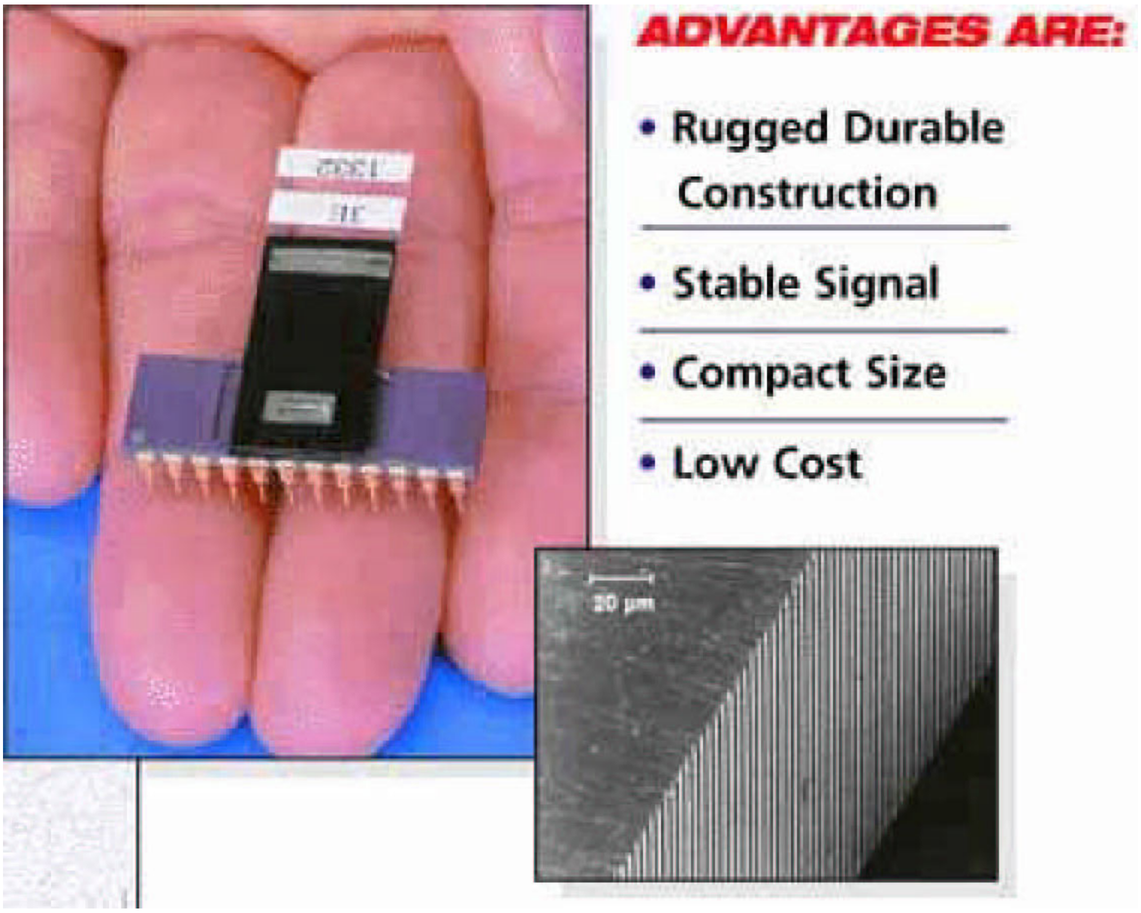
The different categories of Microsystems described previously can be combined to make:

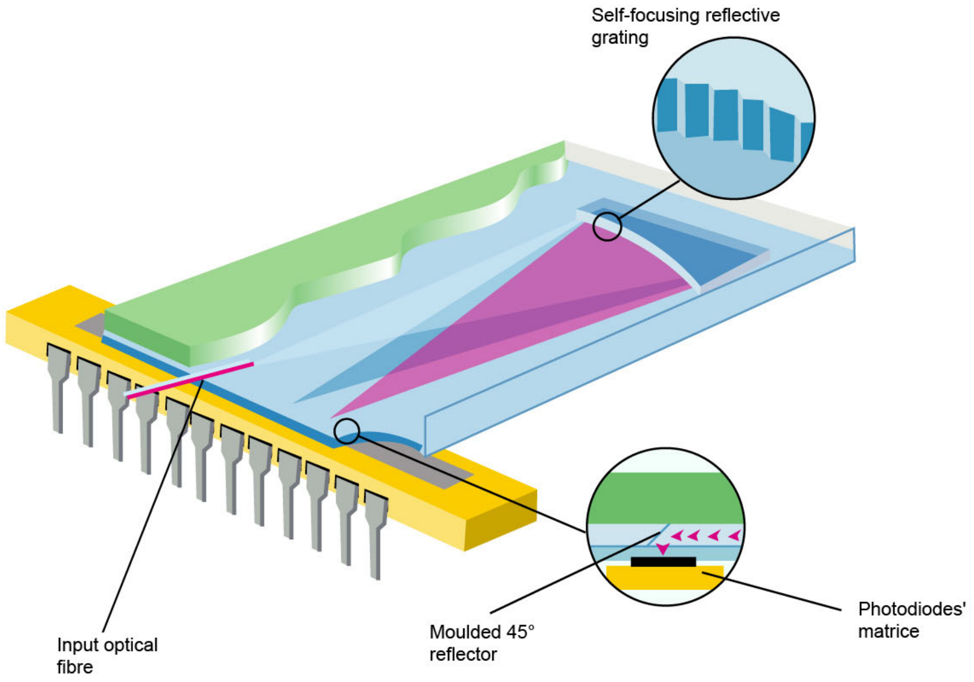
- Optical switches, using, for instance, an interferometric principle in integrated optics;

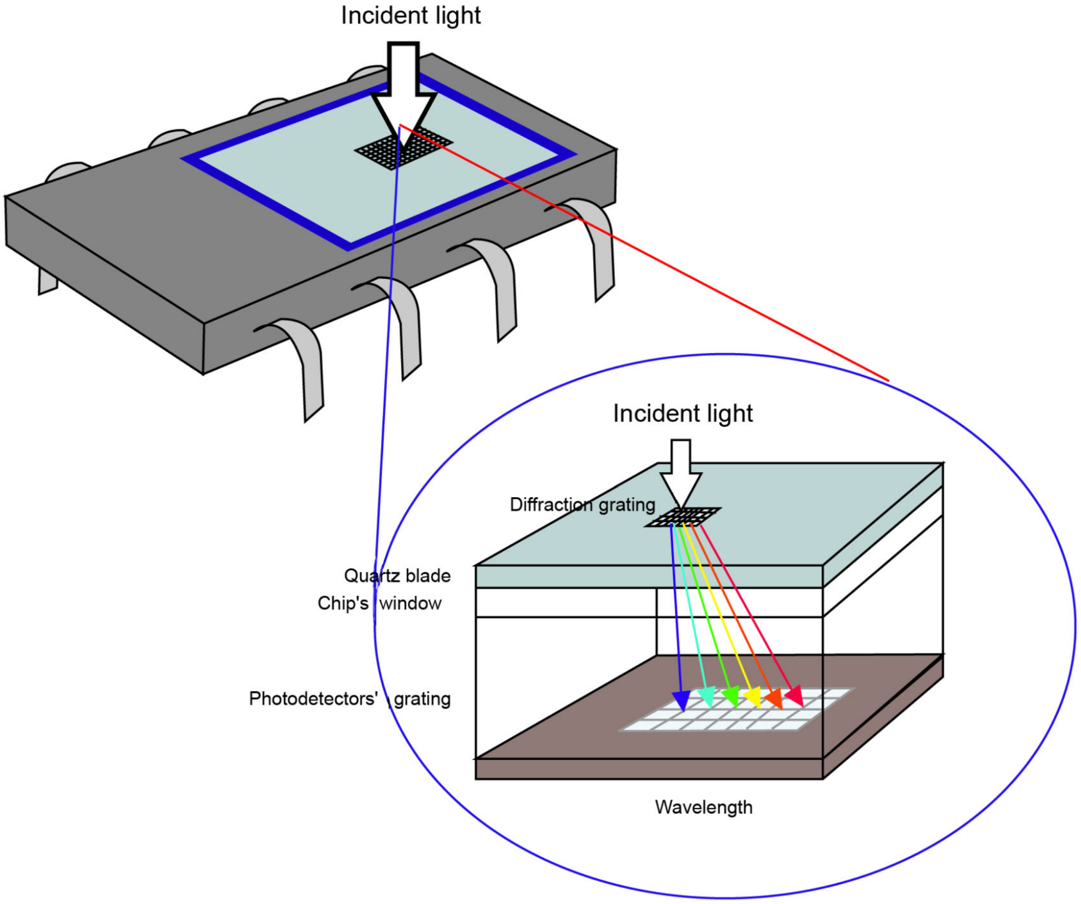




- spectrometers, using Fabry-Pérot interferometers or using, as below, light-scattering by a diffraction grating;







- light modulators, in particular to set up display systems.

3. Short casework

The study of optical Microsystems technologies shows that the same basic technologies have been often used for completely different applications.

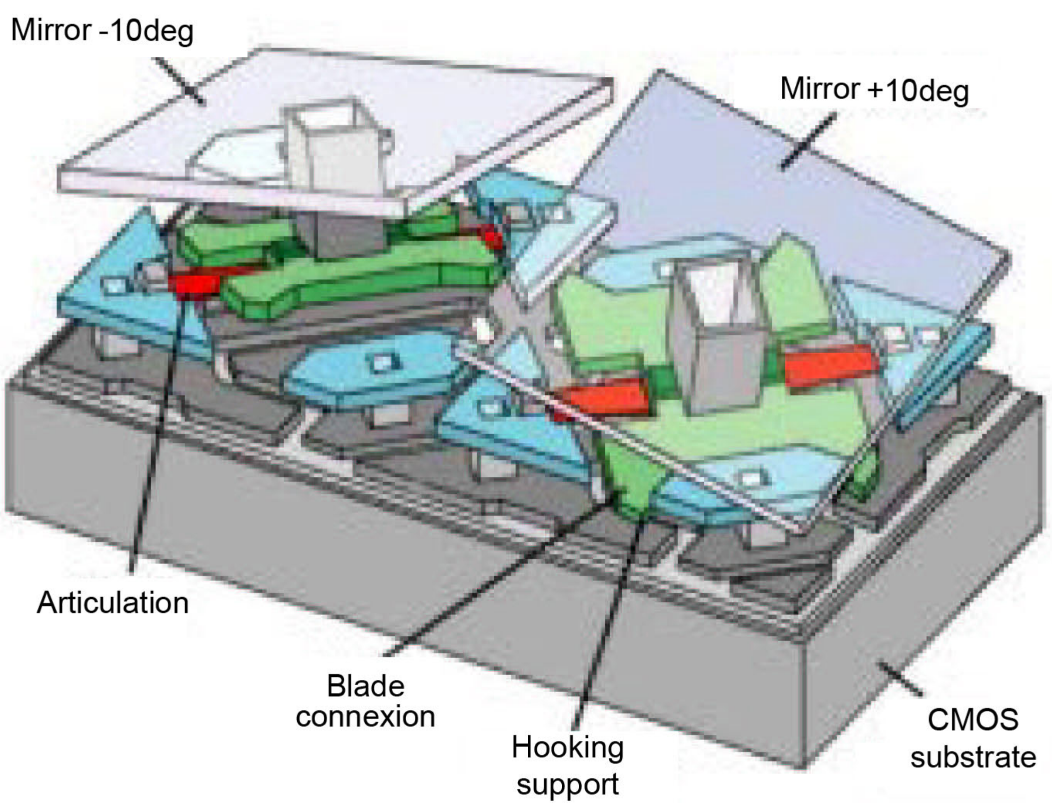
3.1. Digital micro mirrors

In the field of digital information, most of multimedia applications need brighter and larger displays which are at the same time compact and unique. The conventional film projection display systems can't display the digital multimedia information. Many electronic display technologies have been developed since the 1940s. Currently, two main technologies are in cut-throat competition in a fast growing market: DLP technology (Digital Light Processing) and high-temperature polymer LCD projection display technology. The DLP technology is clearly progressing on the big-size expensive projection systems market and on the cheap ultra-portable projector market, whereas the LCD technology is dominating the intermediate market.

Big-size projectors can light up with a flow of more than 5000 lumens on a screen. They are very expensive, heavy and massive and need case in installation and maintenance.

At the heart of a digital DLP projector is a Texas Instruments patent DMD✯ system (see Casework in the Introduction to micro optics lesson), which is made of a micro-mirrors matrix. Each micro-mirror swivels under the influence of an electric field strength acting on the substrate on which it is. According to the slew angle ($+10°$, $0°$, $-10°$), each mirror reflects the light transmitted by the projector lamp in order to make a on/off switching of the light flow so that we can digitally make a gray-scale on 10 bits (104 levels) for each primary color. We get the color image either with color wheels and a DMD device or with dichroic mirrors and combining prisms with three DMD devices for each primary color. The graphic or video input signals are changed into a binary digital code which makes the micro-mirrors hinge.

DMD devices are made of micro-mirrors put on CMOS command circuits according to the layout below:



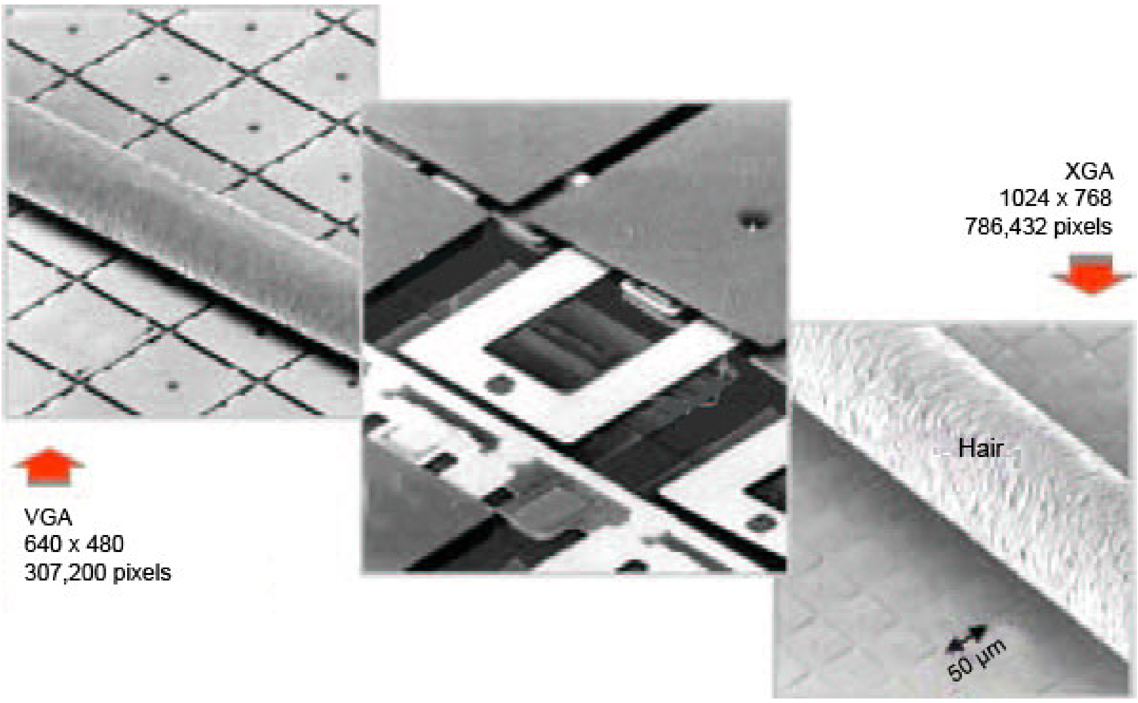
The DMD device is made in one block by a CMOS compatible process. Each micro-mirror is made of a $16\mu m \times 16\mu m$ aluminum layer. The rotation varies according to the axis of the mirror diagonal under the influence of electrostatic gravity.

The biggest technical problem of these devices consists in ensuring mechanical reliability. Due to the high modulation speed, the torsion couple needs a more than 1013 cycles reliability during its lifetime. The defects were progressively solved, thanks to constant enhancements in conception over the past 10 years.

3.2. Thin film DMDs

We can make reflective light spatial modulators thanks to micro mirror matrices, using actuators made of micro-machined piezoelectric film to control the slew angle of each matrix micro mirror in order to define the gray-scale of each pixel in the screen. The reflected light on a mirror surface makes a rectangular shaped image on the projection shutdown screen, which moves along the horizontal axis as the slew angle is changing. When a micro mirror doesn't swivel, all the reflected light is stopped and adsorbed on the shutdown screen and the pixel image on the screen is off. When the micro mirror has swiveled at full capacity, all the reflected light goes through the shutdown screen, the pixel image on the screen is on. The quantity of light going through the shutdown screen is proportional to the tilt angle of each mirror. A specific control of slew angles allows to create grey levels on the screen between the extreme brightness states (on-off). Therefore, thin film micro mirror systems share the functional necessity to create matrices with a DMD system, on which they add the necessity of the nanoscale control of the precision positioning for gray-scales

Each pixel consists of a bilayer structure: a mirror and an actuator layer. The mirror rotation is ensured by a piezoelectric thin film actuator in the form of clamped micro beam. As you see in the photograph below, a mirror is connected to the lower clamped micro beam thanks to a suspension arm.



The beams are tied to the PMOS substrate. Each clamped beam consists of a non-stoichiometric silicon✯ (SiN$_x$) nitride layer, which is used as a support for a platinum inferior electrode, a piezoelectric layer and a platinum superior electrode. When there is voltage between the two electrodes, the piezoelectric layer contracts in the horizontal direction and dilates in the vertical one. As a result, the beam neutral line moves forward the inferior electrode due to the layer of the thickness of the basis layer, and the mechanical contraction of the piezoelectric layer produces a vertical refraction of the beam upwards and as a consequence, the inclination of the mirror on it.

Thin film micro mirror matrix devices are made in one block on active PMOS matrix through surface micro-machining techniques. The active matrix is a transistor network sending a video signal to each pixel. The size of each mirror is $49\mu m \times 49\mu m$ for XGA systems.

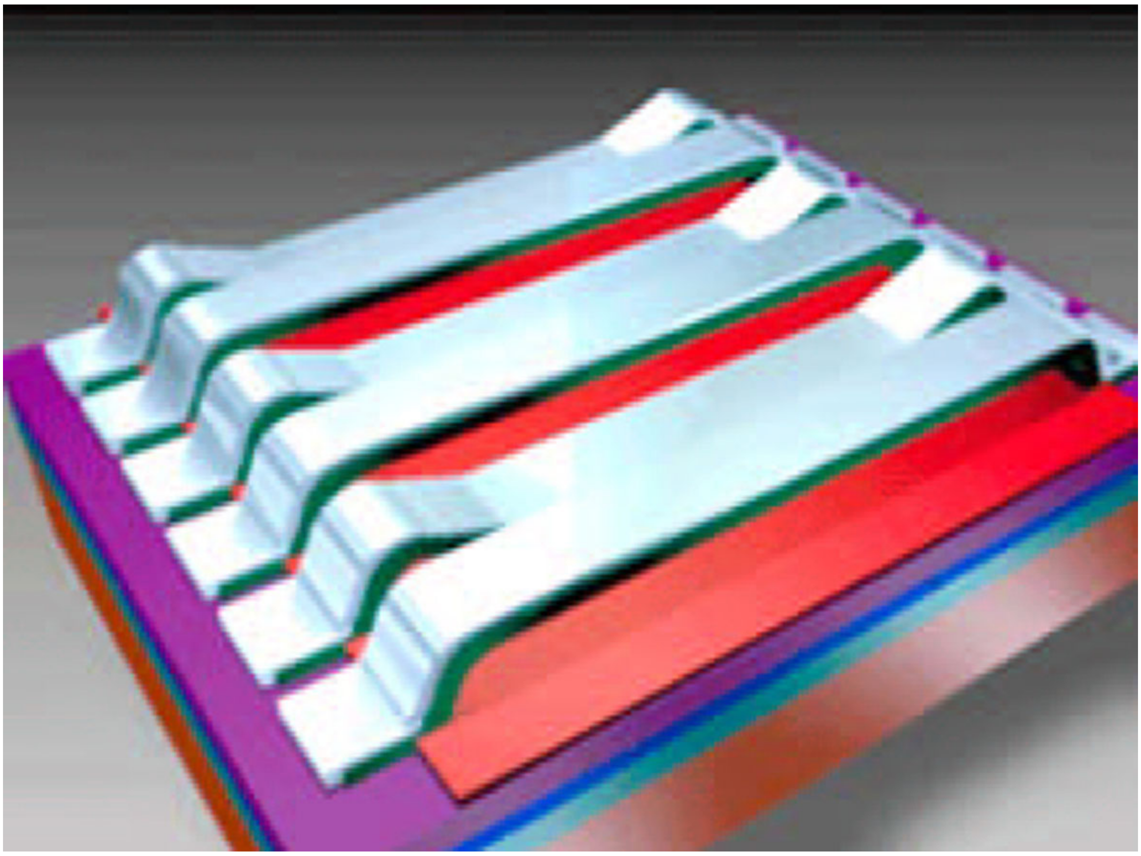
The aluminum is sprayed on the upper sacrificial layer of mirror layers. Aluminum layer is micro-machined with dry etching to shape mirrors. Sacrificial layers are put off to make the needed air gaps. As we must use two different materials for these layers, the crowning process has two steps. First, the superior sacrificial layer is cleared through the gaps between reactive ion etching mirrors. Then, the complete crowning of this layer is done, and the sacrificial layer is exposed to the air and is eliminated by a xenon fluoride vapor etching. These two techniques have high lateral etching speeds, don't produce any residue, don't etch nor damage the other layers. The picture above deals with electronic microscope snapshots completed by VGA and XGA matrix after the sacrificial layers release process. The 800 000 final mirrors of t XGA device show initial inclination positions of $0^\circ \pm 0.03^\circ$.

A 5 400 lumen operational projector prototype with 3 thin film micro mirror matrix systems and a $1kW$ xenon lamp was presented during the 1998 Asian Display Fair, and offered a light transmission overall efficiency of 22%.

The clamped piezoelectric micro beam actuators of thin film micro mirror matrices were used not only for the display but also for the quick scanning of AFM probe matrices and the adaptation of mechanical constraints in photonic devices.

3.3. Grating Light Valve

The GLV✯ is a specific Microsystems application working as a dynamic tunable grating to change precisely the quantity of diffracted or reflected laser light. The GLV is made of many tapes on the surface of a silicon plate (see the picture below). These tapes can move upwards or downwards on very small distances by adjusting the electrostatic forces between the tapes and substrate. Due to the positioning of the tapes, each element can reflect and diffract light, so that a well positioned matrix can make the level of reflected light on the plate vary. The light control can be analogical (variable control of the light level) or digital (on/off switching). As the GLV devices use the diffraction principle to switch, dim and modulate light, they are very precise, are easy to produce and can possibly manipulate relatively high power beams. However, as the projected light is obtained by diffraction instead by a direct reflection, there are obviously some losses towards incident power.



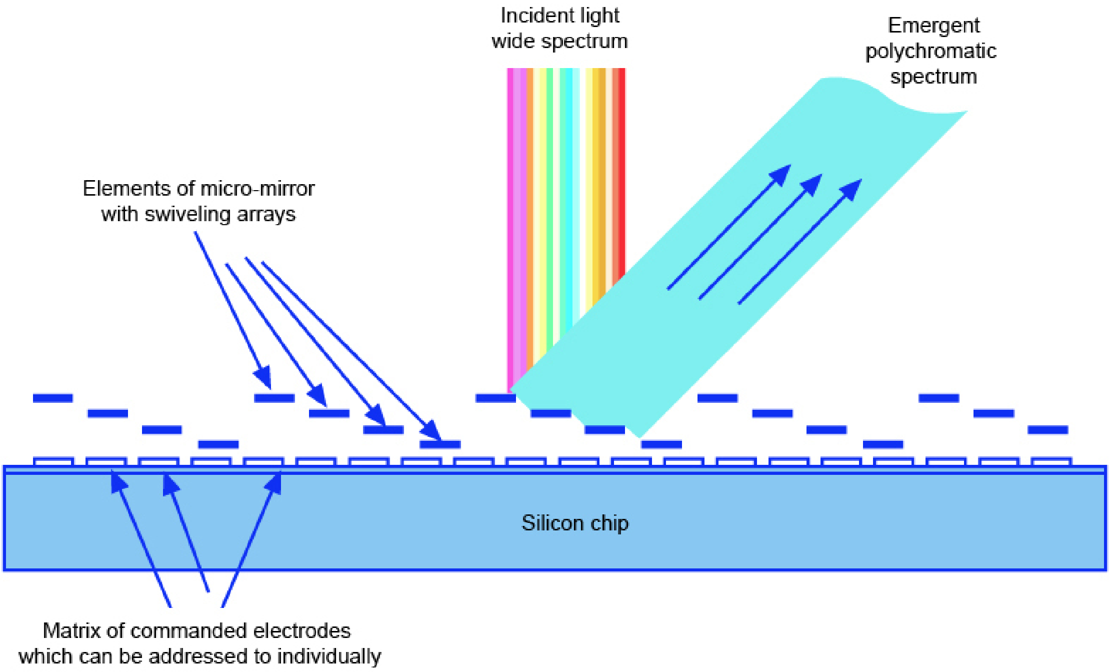
Each GLV✯ component is made up of 6 parallel tapes are suspended at both ends and made on silicon nitride covered with a reflective metal layer. This superior layer also acts as an electrode to create an attractor electric field strength with the inferior electrode shared by every tape. It takes $20ns$, which is much more faster than with the current pivoting mirrors. The current devices are said to have a diffraction efficiency near to the81% theoretical maximum, a 95% filling factor and a 91% superior electrode reflective ratio, with an overall efficiency of devices of about 70%, corresponding to insertion losses to the order of $1.5dB$.

Large size projection displays were the first applications affected by GLV technologies. We showed that a projection display, in order to show a high definition TV image of 1920×1080 pixels, could be made by the scanning of a 1080 pixel linear GLV matrix. But because of the commercial competition between DLP and LCD devices and the price war that followed, the additional costs of the scanning system and the speckle effect due to the laser beam led to a postponement of GLV screen marketing. But the GLV digital accordability allowed to use with success many reconfigurable optical devices such as tunable filters, dynamic gain equalizing filters and GLV printers.

3.4. Polychromators

Polychromator is a darkness field correlation spectrometer system, electronically programmable and based on an optical micro system made of a programmable grating. This device was implemented as part of the collaboration between Honeywell, the MIT and Sandia National Lab. Instead of being a means of displaying images, the polychromator is a new sensor system able to distinguish between many gaseous species from a distance by using a combination of optical systems and MOEMS✯. This device also allows a sufficient sensitiveness and selectivity to detect very weak quantities of gas for imagery applications for biology and security.

Polychromators don't need reference cells unlike numerous conventional techniques of gas analysis. For this, the reference spectrum for each measure is get thanks to the modulation of the polychromator grating. The latest devices consist in thousands of mechanical beam components on a silicon plate. Beams and actuators are made according standard techniques of thin films development. Each grating component is $10\mu m$ wide and 1cm long and is developed to move vertically upwards or downwards as in the picture below:

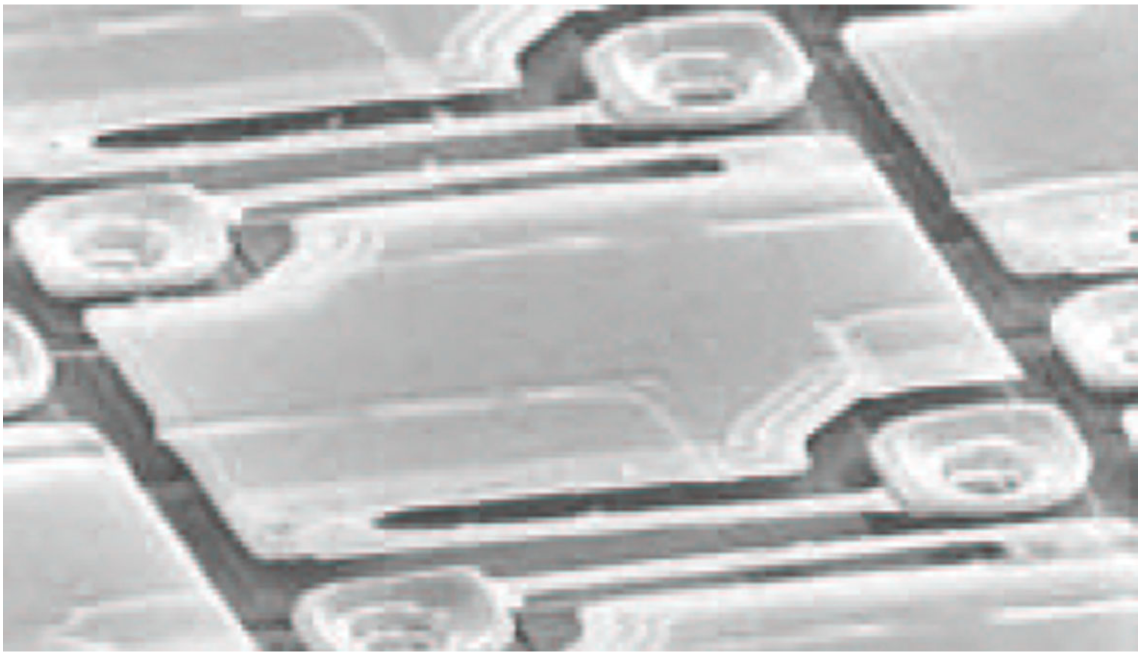


The light coming from the environment (for instance the light from a suspect gaseous cloud) is led to the sensor after being collected by an optical relay like a telescope or a binocular scope. Then the grating is planned to bring together the incident spectrum to a reference spectrum. That's the way we know if the gaseous cloud contains the substance that the grating needs to go work. Of course, the main feature of the device is its capacity to be reset. So the polychromator replaces a whole row of gas cylinders containing reference chemical products which should have been used to implement a correlation spectrometry technique.

3.5. Infrared non-cooled bolometers

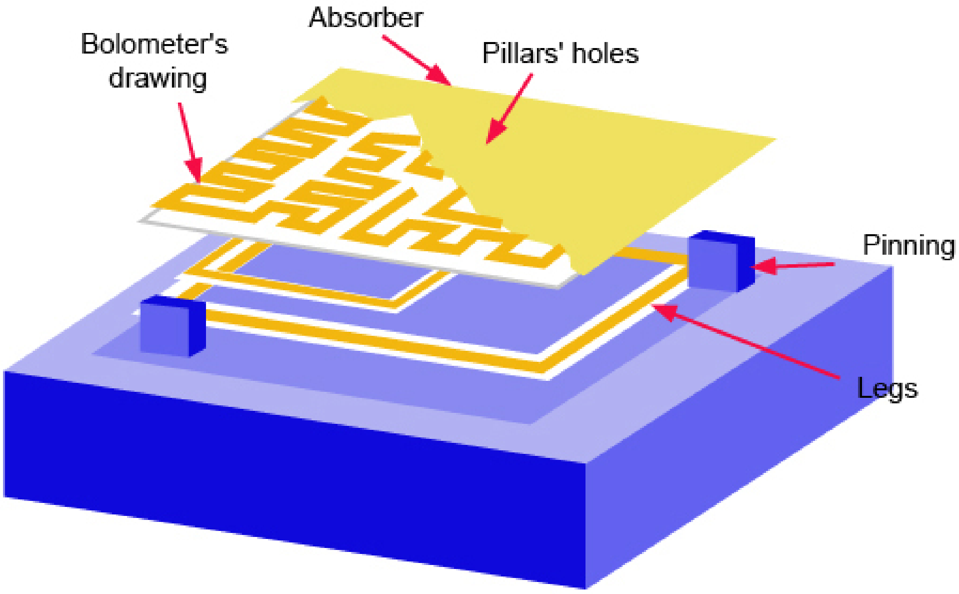
Infrared sensors allow to identify and represent objects according to their emission temperature. Thanks to thermal imaging we can measure the temperature at a distance and have the possibility to see in the dark, in smoke and when the weather is very cloudy. Until a few times ago, high performance IR✯ cameras required very expensive systems without cooling that went until cryogenic temperatures to detect photons and eliminate thermal noise. More recently, sensor working at room temperature has been developed using micro machined bolometers and pyroelectric detectors. FPA✯ (Focal Plane Array) infrared structures can produce infrared images or objects for sets made by human beings transforming the led temperature changes into electrical signals. Non-cooled bolometers use the led changes by temperature in electrical resistance, polarization and dielectric properties of the material composing detectors.

These detectors need a high thermal insulation with the substrate to get a high sensitiveness. Micro technologies play an important part in the manufacture of such weak specific heat capacity detectors with a thermal insulation exceptionally high. Honeywell is marketing a resistive bolometer 2D matrix with an insulating structure (see picture below).



The nitride silicon membrane is suspended by two arms above the silicon substrate. The size of the suspension arm is calibrated in order to have a thermal conductivity of $8 \times 10^{-8} W/^{\circ}K$. The plate specific heat capacity is $8 \times 10^{-10} J/^{\circ}K$ and the response time in temperature is $10ms$. Working at a pace of 30 frames per second with a $f/1$ optics, the NETD (Noise Equivalent Temperature Difference) has been measured at $0.04^{\circ}C$ with vanadium oxide resistance. Another alternative consists in developing a 2D monolithic matrix by using the pyroelectric properties of lead titanate with an insulation system similar to the one developed by Honeywell. The NETD announced for this device was $0.01^{\circ}C$ and was adopted for several similar applications.

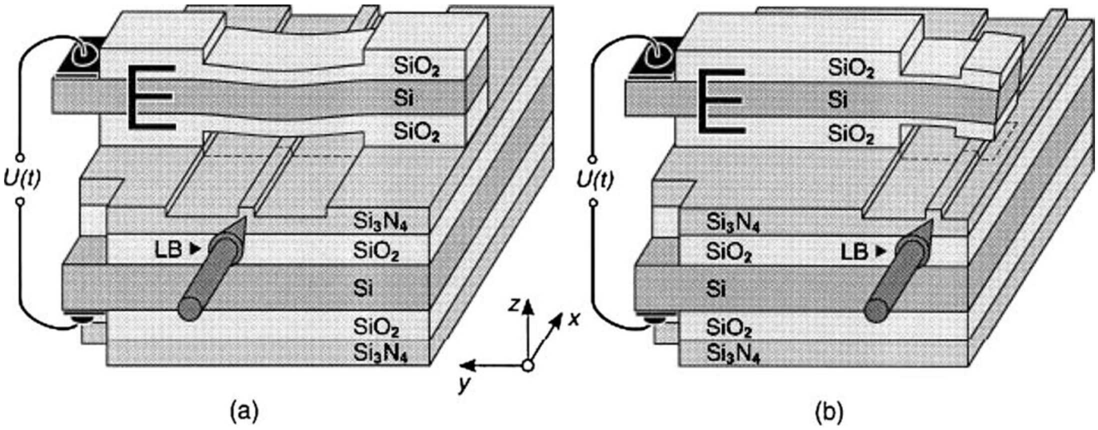
On the photo below, you can see a three level device manufactured by Kim and his team.



The main goals of this device were to increase the filling factor (92% against 62% for the Honeywell device) and to minimize thermal conductivity, similar to that of the Honeywell planar device.

3.6. Microsystems for integrated optics

Optical micro systems described previously can be considered free-space optical systems as the mobile structures (mirrors, gratings, etc.) interact with light during its spread in the air. On the contrary, in integrated optics, light is contained in waveguides carried out on the appropriate optical materials, such in the picture below.



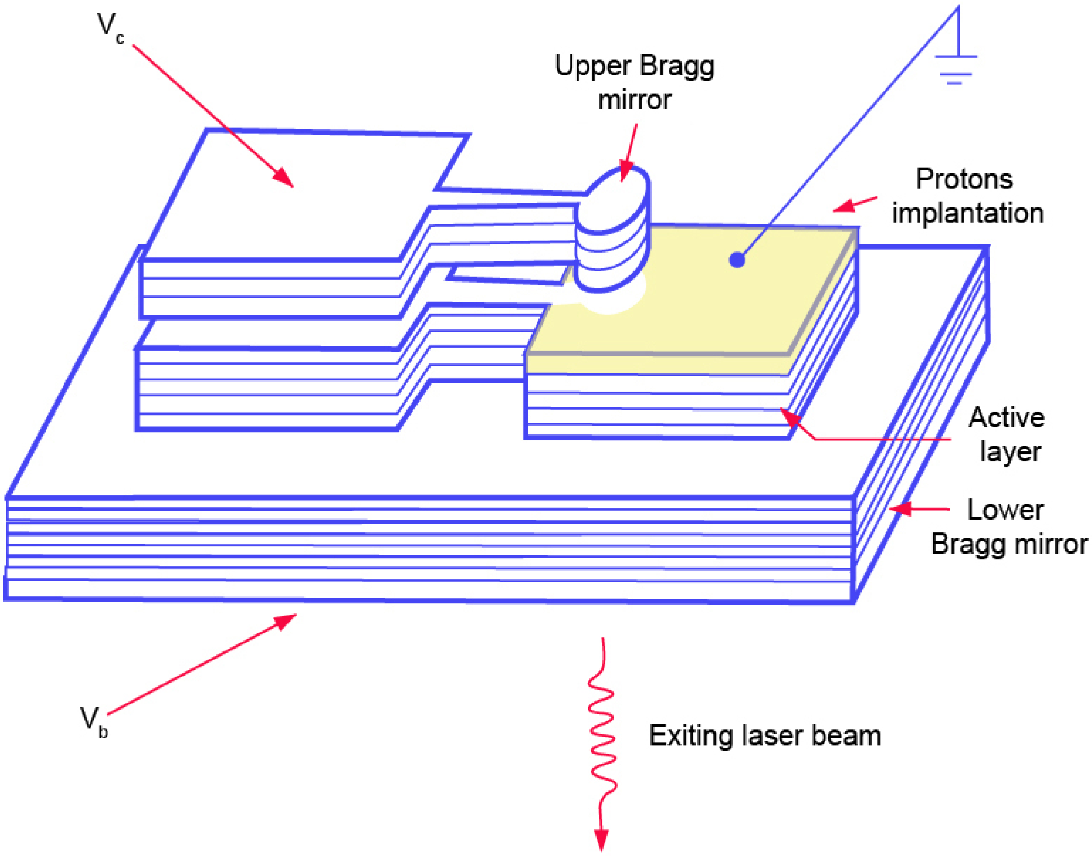
In this case, it's obviously hard to control the propagation of light with mirrors or diffraction gratings upon direct contact with the light beam. However, there are other means to control light, with mechanical structures in integrated optics. They are based on the coupling by evanescent waves between guided light and dielectric structures such as bridge or beam gantry, suspended on waveguides. Basically these devices are phase modulators and work by modifying the guides refractive index, modifying so the light group speed.

For instance, we can make a 2×2 optical switch on the basis of a Mach-Zehnder interferometer in which the phase delay is controlled by a micro system using the phase modulation.

3.7. Tunablecavity Fabry-Pérot laser

The possibility of nanopositioning is essential for applications such as the tunable laser cavities for which the specific dimensions are in the order of the laser wavelength. This necessity allowed a good combination between MOEMS✯ nanopositioning capacities and VCSEL✯ technology. VCSEL were invented during the late 1980s, they were a means to obtain solid-state lasers to give out light vertically compared with a substrate, which is better for a high number of applications in lighting, optical networking, etc.

In initial structures, the VCSEL upper mirror was a DBR (Distributed Bragg Reflector). In the Microsystems setup described in the picture below (from 1995), the reflector is linked to a mobile clamped beam structure, able to grant the resonating wavelength until 15nm with a weak voltage control of approximately 5 to $7V$.

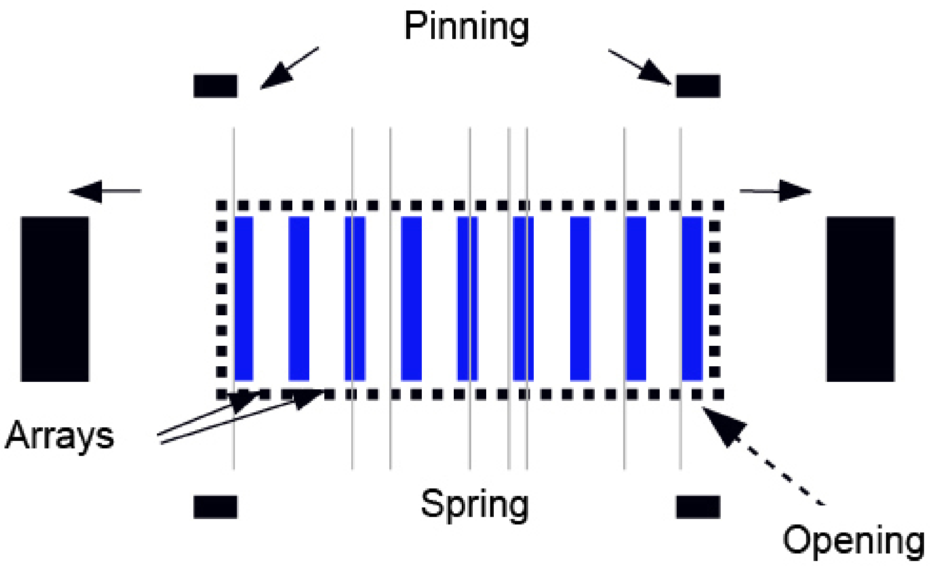


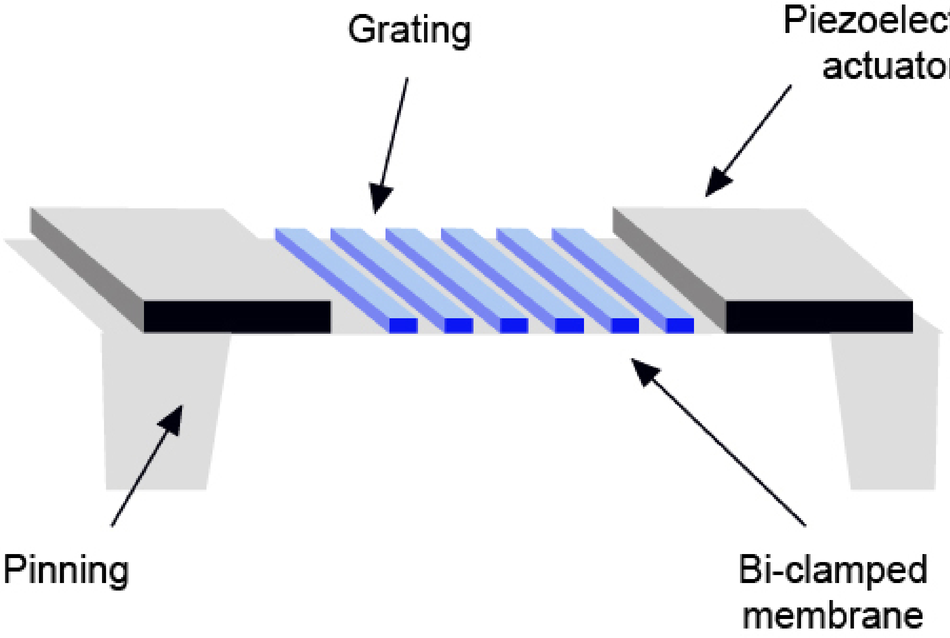
Since the first experiences, acordability has been improved in order to cover the $1530-1620nm$ range of DWDM✯ communications wavelengths.

3.8. Optical devices tunable strains

Tunable gratings like GLV✯ or polychromators can be considered digital systems as the actuation is the result of a change in the grating period and its profile modulation in tiny quantities, with the same size as micro machined tapes. Since then, the "reconfigurability" is limited by the smallest dimension allowed by the lithography process. To open very small scale possibilities, it was necessary to implement a new range of "analogical" tunable grating. Nanopositioning was an additional functional possibility given by these devices, necessary to allow a rather precise reset for optical applications. But another aspect is sacrificed as these analogical devices are not appropriate, for instance, to have polychromators functions in a correlation spectrometry.

Diffraction grating analogical scanning is get by a transverse activation of the grating structure by using a piezoelectric thin film actuator or interdigitated electrodes with folded up grating, as in the picture below.





To get the transverse actuation, the grating etchings are made on a deformable membrane in suspension. The membrane is mechanically tightened by thin film piezoelectric actuators made of a lead zirconate titanate between two superior and inferior electrodes, located at the ends of the membrane. These piezoelectric actuators can produce a power strong enough to stretch the membrane until a 0.3% constraint or until producing a 0.3% variation of the diffracted angle under the influence of an electric field across the piezoelectric film. The tenseness of the piezoelectric film leads to a mechanical constraint on the membrane in the transverse direction.

Considering the possibility of a very precise control of the voltage on a piezoelectric thin film, we can get a resolution better than $0.05nm$ in the period variations of the grating corresponding to an angular resolution better than $2.1\mu rad$ whereas the current possibilities of metrology do not permit an observable resolution inferior to the nanometer scale. Membrane rotations and torsions outside the balance plan, the asymmetrical rotations during the actuation, thermal disturbance, vibration and optical detection techniques can limit the thinnest available resolution. The display of tunable diffraction gratings allowed to see the accordability of the diffraction angle from the first order until $486\mu rad$ under $10V$ with minimal movements observable from the grating period of approximately 0.6 under $1V$.

Reconfigurability combined with nanopositioning lead to interesting application possibilities for accordable grating devices.

Exemple

For instance, ultra-precision devices can balance the wavelength thermal drifts in optical communication grating, sensitive to temperature variations such as multiplexers/demultiplexers and routers.

Remarque : "Optical diversity" technique

We can notice that we can make diffraction grating device matrices, in particular with piezoelectric devices in which actuator only have a few role in comparison to electrostatic devices.

The “optical diversity technique” is another interesting way that has been developed to balance the limitation of the grating spectrometers opening. In a few words, here is the problem: the spectral resolution of a grating spectrometer is determined by the number of N periods of the grating. So, as the available surface is (by definition) very small in a miniature spectrometer, the spectrum we get can be blurred. In other words, the measured value of the spectral density at one wavelength doesn't correspond to real value of the tested sample but it also has contributions from other neighboring wavelengths (this is call the convolution phenomena). Of course we can go back the real spectral density thanks to a deconvolution operation, knowing the impulsional response of the grating which depends on N and the impulsional response of the light collection optics. This deconvolution can be made digitally with a post-treatment of the measured spectrum. But the deconvolution operation is very sensitive to noise inherent in every measure. We found out that, by scanning the grating and repeating the spectral measure, we could get the blurred spectrum back with a much more weak sensitiveness to noise and, as a consequence, a so much better definition.

Optical diversity works that way: the grating period is first fixed to an initial value and a first blurred measured is taken. Then the grating is activated in such a way that the period is changing of a few quantities and a second blurred measure is taken. We repeat this process according to the noise we heard. The weaker the signal-to-noise ratio is, the greater the number of necessary measures is. Then the group of get spectra is treated by using a class of mathematical operation called “regularized pseudo-inverse method”. After this step, we get the final spectrum. The quality of the signal treatment process is linked to the measure noise level and to the grating actuation precision and definition. It emerges that optical diversity is a good example to show how reconfigurability and nanopositioning can help to solve an important optical problem due to spectrometers miniaturization.

4. Which materials for which applications?

4.1. Reminder

We have seen that micro-machining makes the manufacturing of miniature mobile structure suitable to optical applications possible. Very small movements, for instance of a quarter wavelength in an interferometer, can make an on/off switching or create modulation effects more important than in conventional electronic or electro-optical devices. Likewise, we saw that micro mirrors gratings can be the basis for display systems or optical routers.

At the same time, the miniature optical devices have to meet a certain number of dimensional and structural constraints that can be more important than those weighting on other Microsystems.

Exemple

- Surface roughness determines mirror reflectivity.
- Mechanical constraints on membrane create distortions in reflected images.
- Integrated waveguides in optical Microsystems must have reproductive refractive index and optical losses.
- Actuators, which can be electrostatic, piezoelectric or thermo-mechanical, must have an actuation voltage and a weak energy dissipation while ensuring a reproductive performance on a large range of performance cycles.

So, it's really important to correctly choose the materials and manufacturing techniques.

4.2. Example of DMD projection display systems

If we take as an example DMD✭ projection display systems developed by Texas Instruments, we notice that instead of using a surface micro-machining conventional process with a phosphosilicate glass for the sacrificial layer and polysilicon for micro mechanical components, we developed a low temperature process using a conventional positive resin and aluminum alloy applied by spraying. This process made possible the manufacturing of every electronic underlayer of micro mechanical components under mirrors, thus allowing to have a high space factor and small air gaps under micro mirrors.

In order to ensure a high reliability, we particularly took care of reducing the pinching between the parts in contact with each other. For this, a lubricant self-assembled monolayer is applied to reduce the Bonding Force. Moreover, we use an electronic feedback to pilot and control micro mirrors movements in order to avoid shocks and oscillations. A specific aluminum alloy has been developed to minimize micro mirrors angular drifts in time.

If we take in account that these devices have more than one millions micro-mechanical component and that the human eye is able to detect while reading a small number of defective pixels on a screen, we perfectly understand why packaging had to be made in ISO 4 cleanroom instead of ISO 7 cleanroom to eliminate the defects due to particles from outside devices.

Clamped micro beams, membranes and micro bridges are often subject to constraints, in particular when thin films are laid on their surfaces. These constraints can be intrinsic (mesh mismatch for example) or due to thermo-mechanical effects linked to differences in material thermal expansion coefficients. They often lead to structural deformations outside the mirror plan with unpredictable angles.

Exemple

Researchers proposed a 2×2 optical switch based on a polysilicon clamped micro-beam with a pivoting micro-mirror in normal position, outside of the plan because of a thin film of a gold-chromium alloy putting the polysilicon in a compression state. The switching is actuated by applying a tension between beam and substrate, so that the micro-mirror is on the light way.

Micro-mirrors used for telecom routers are basically covered with gold, which has excellent reflective properties in infrared environment. But we have to pay attention not to contaminate with gold electronic devices on silicon integrated in structures.

We often use silicon nitride to make an optical waveguide with many techniques, among them spraying, CVD, PECVD and LPCVD. The technique used and the process precise condition both contribute to the variations of refractive index, optical losses, amplitude and nature of the residual stress. For instance, by using the PECVD technique, we can get refractive index between 1.9 and 2.2 with variable stress in compression or in tension according to the Si/N atomic ratio and the deposition conditions. It emerges that the choice of materials and implementation conditions must be done very carefully to ensure stable and reproductive structures.

4.3. Other examples

In addition to passive optical material like Si3N4, and according to applications, it turns out to be very interesting to use active materials such as electro-optical or magneto-optical materials for optical modulation, pyroelectric materials such as IR sensors or fluorescent materials to make the sources. Most of these interesting active materials are complex oxides, often made up of perovskite structures which, normally, in a massive solid state, have to reach high temperatures to obtain the phase purity or the desired micro-structures. In order to make their integration possible in the structures of silicon micro-electronics or on micro-mechanical devices, these materials are set up in the form of thin film, either by vapor phase deposition techniques (for instance by pulverization, PLD, MOCVD, MBE) either by chemical methods (for instance the sol-gel process). In general, the degree of crystallinity, orientation, micro-structuration, stoichiometry and intrinsic stress depend on the deposition conditions, the substrate nature and temperature. In most cases, the film made show a reduced activity compared with the corresponding massive material. For instance, an electro-optical modulator get by laying a BaTiO3 film on a MgO single-crystal substrate shows an effective electro-optical coefficient of $50pm/V$, less than an order of magnitude weaker than the measured value for the single-crystal. We notice a similar phenomenon for piezoelectric properties. These phenomena are said to be due to stress effect imposed by the substrate, by the defaults and at the interfaces level. Stamp layers, between silicon and active oxides, have an essential role to avoid interdiffusion and oxidation but they also act as “germ” layers to help the phases nucleation and appropriate crystallographic orientations. There is an excellent journal about many of these problems in an article written by P. Muralt in 2000 (Journal of Micromechanics and Microengineering, Vol 10, p 136).

4.4. Outlook

As we already mentioned it in the introduction, miniaturization is not enough to create new opportunities for optical Microsystems. The collection of devices we talked about in this lesson was not thorough but gave indications about the possibilities provided by the new functionalities such as the networking, reconfigurability and nanopositioning. Future information technologies need communication networks always faster and smarter we only can obtain from “all optical” systems with more sophisticated optical functionalities, such as intelligent optical signal treatment or adaptative optics.

III.References

1. Acronyms

MEMS: Micro-Electro-Mechanical Systems
MOEMS: Micro-Optical-Electro-Mechanical Systems
Si: Silicon
Ge: Germanium
IR: Infra-Red
MOS: Metal-Oxide-Silicon
WDM: Wavelength Division Multiplexer
DWDM: Dense Wavelength Division Multiplexer
VCSEL: Vertical Cavity Surface Emitting Laser
FPA: Focal Plane Array
GLV: Grating Light Valve
DMD: Digital Micro mirror Device

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Signification des abréviations

- DMD	Digital Micromirror Device
- DWDM	Dense Wavelength Division Multiplexer
- FPA	Focal Plane Array
- GLV	Grating Light Valve
- IR	Infra-Red
- MEMS	Micro-Electro-Mechanical Systems
- MOEMS	Micro-Optical-Electro-Mechanical Systems
- Si	Silicon
- VCSEL	Vertical Cavity Surface Emitting Laser