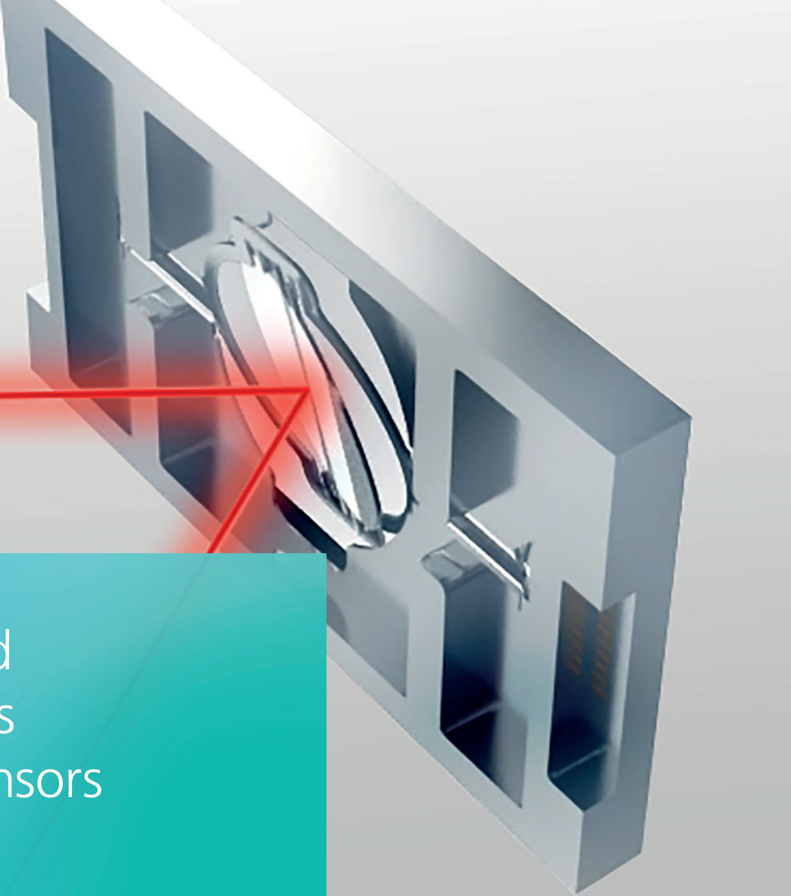
Fraunhofer IPMS



MEMS mirrors – resonant and non-resonant optical scanners with integrated deflection sensors

Fraunhofer IPMS has many years of experience in the development of customized silicon MEMS scanners. These devices comprise an optical surface – a mirror or a diffraction grating – which can be tilted around one or two axes of rotation, or which can be linearly displaced. Actuation can be implemented in resonant or non-resonant mode. A combination of the two types is possible as well.

Non-resonant MEMS mirrors can perform an arbitrary trajectory, e.g., with triangular, serrated, or stepwise shape. In particular, they can be set to a static deflection. Resonant MEMS mirrors are operated close to their resonance frequency, defined by design. They make use of a high quality factor to achieve large deflections.

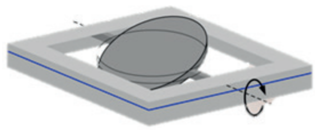
The variety of available scanner designs is characterized by a large optical scanning range, a broad region of operational frequencies, different mirror geometries, and various optical surfaces. The silicon MEMS mirrors are extremely reliable. They are equipped with a monolithically integrated deflection sensor system for precise acquisition and control of their mechanical movement. The standard reflective coating of IPMS MEMS mirrors has a reflectivity of approximately 90 % in the visible range. It is also possible to apply a customized, highly reflective dielectric coating.

IPMS MEMS mirrors are manufactured in bulk micromechanics from monocrystalline silicon. The CMOS-compatible process is qualified and suitable for series production. The range of applications is continuously being expanded by innovative and patented design solutions as well as application-specific technology modules. Fraunhofer IPMS has developed more than 200 different microscanner designs. They were fabricated in its own clean room facilities.

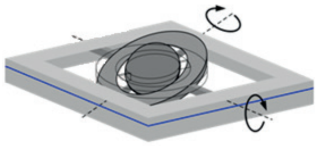
The portfolio in the field of MEMS mirrors is rounded off by evaluation kits, customer support in the development of specific module designs, and electronics solutions for controlled actuation that exploits the precision of the scanners.

Selection of MEMS microscanner designs

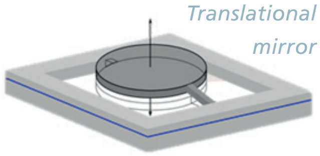
1D tilting mirror



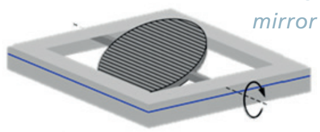
2D tilting mirror



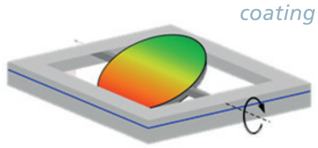
Translational mirror



Grating mirror



Highly reflective coating



Design spaces and parameter examples of 1D and gimbal 2D MEMS microscanners

Gimbal MEMS scanners and parameter examples

Type	Mode	Parameter ranges of different designs			Parameters of selected sample designs		
		Mirror size (1)	mech. Amplitude (2)	mech. Resonance (3)	Mirror size (1)	mech. Amplitude (2)	mech. Resonance (3)
Tilting mirror 1D	quasi-static	1 … 6 x 8 mm²	up to 10.5°	up to 2.4 kHz	2 x 3 mm²	9.5°	550 Hz
	resonant	0.5 … 7 mm²	up to 25°	up to 100 kHz	3 x 3 mm²	9.5°	6.0 kHz
Tilting mirror 2D	quasi-static | resonant	up to 5 x 7 mm²	up to 10° | up to 22°	up to 1.2 kHz | 37 kHz	2.5 x 1.8 mm²	10° | 17°	180 Hz | 4.5 kHz
	resonant | resonant	up to 3 x 4 mm²	up to 28° | up to 21°	up to 25 kHz | up to 42 kHz	3.3 x 3.5 mm²	11° | 8°	150 Hz | 110 Hz
Translational	resonant	-	-	-	D = 5 mm	+/- 500 µm	500 Hz
	quasi-static	-	-	-	D = 5 mm	stroke 120 µm	440 Hz

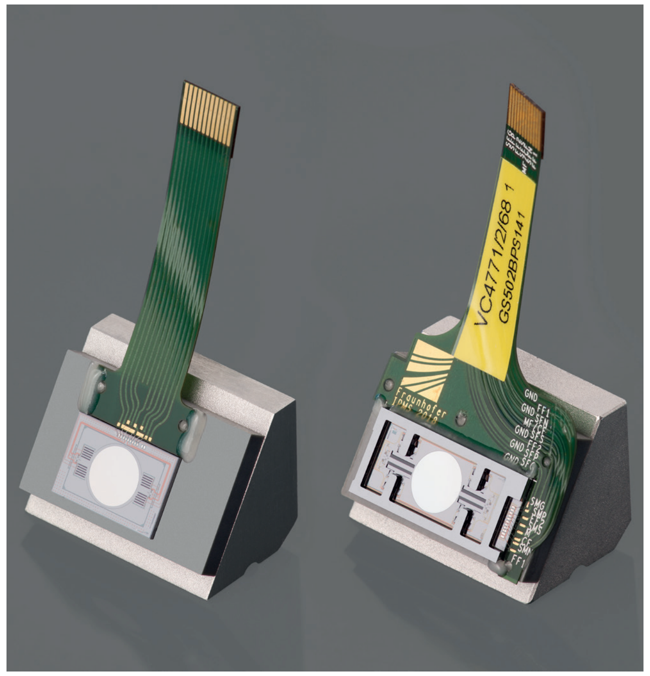
1) Typical mirror geometry: round/elliptical, rectangular for selected designs
2) Amplitude: torsional scanners – Mechanical scan amplitude (mechanical scan range = 2x amplitude, optical field of view = 4x amplitude), translational mirrors – oscillation amplitude (total mechanical displacement = 2x amplitude, optical pathlength modulation = 4x amplitude)
3) The maximum repetition rate of linearized trajectories of non-resonant / quasi-static scanners is about one fifth of this value.

Design spaces for 1D resonant and non-resonant mirrors

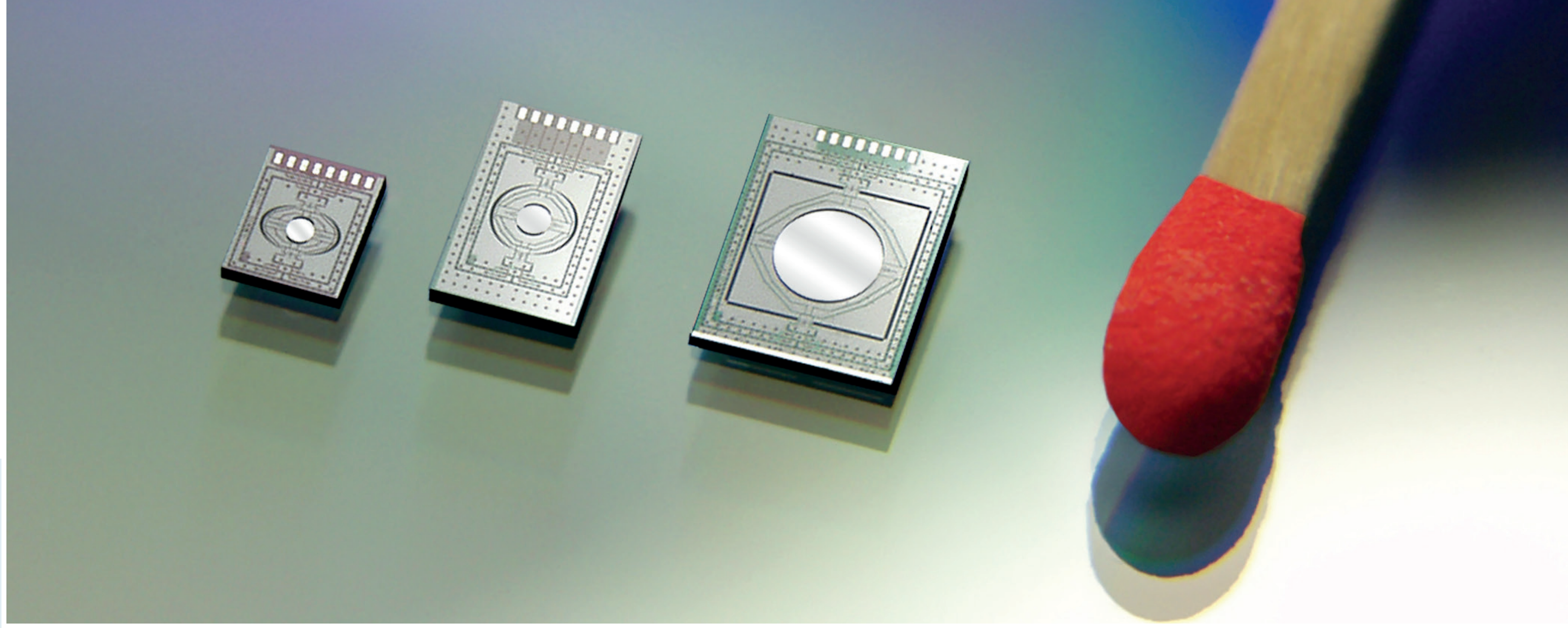
The parameters mirror diameter, natural frequency and deflection are important and mutually limiting variables. In addition, other parameters such as optical planarity, shock and vibration resistance as well as the lowest possible drive voltages and chip dimensions must be taken into account during the design and layout process.

The table above with the microscanner design examples and the listing of resonant and quasi-static design spaces provides an initial orientation with regard to the feasibility of design ideas. Special cases outside these outlined design spaces are also possible. These are typically evaluated as part of feasibility studies. For the resonant design space, the design freedoms increase significantly for natural frequencies below 2 kHz. In addition, a non-resonant frame axis can be combined with a resonant mirror axis as a gimbal 2D MEMS scanner. For electrostatic 2D MEMS scanners with two non-resonant axes, the information in section 2D vector scanners on page 6 applies.

Get in touch with us to discuss your specific application.



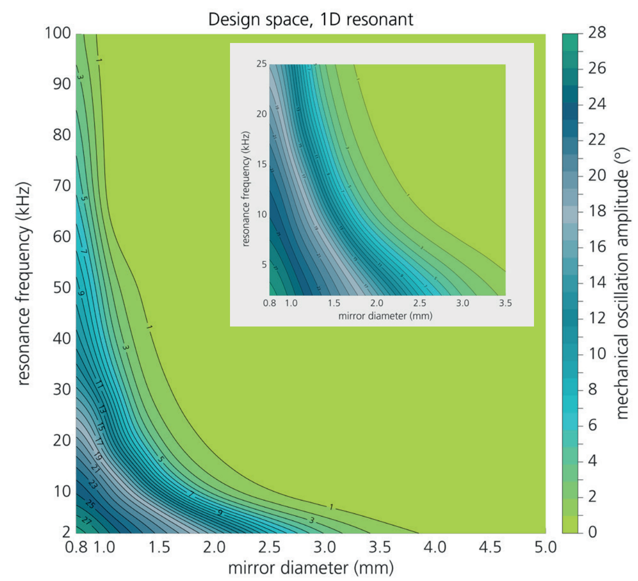
1D MEMS scanner, identical aperture 5 mm
left: 1D resonant, right: 1D quasi-static



Resonant MEMS scanners with small mirror aperture

Design spaces for 1D resonant MEMS scanners

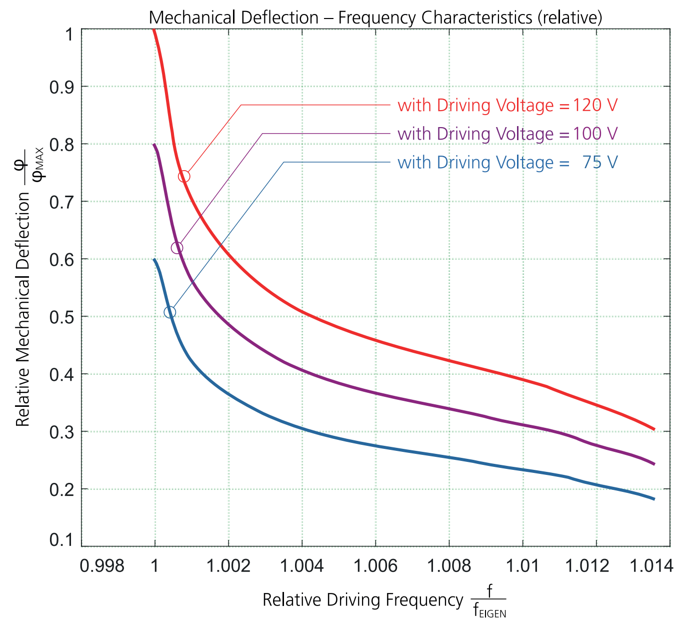
At higher operational frequencies, attention must be paid to the dynamic deformation of the mirror plate, depending on the application and wavelength used. This means that the deformation of the mirror plate must be sufficiently small so as not to negatively affect the beam quality of the reflected light. A maximum value of 100 nm has been assumed for this deformation for the design spaces presented here. For a specific customer design, we take into account the tolerable value for the respective application in the design simulations.



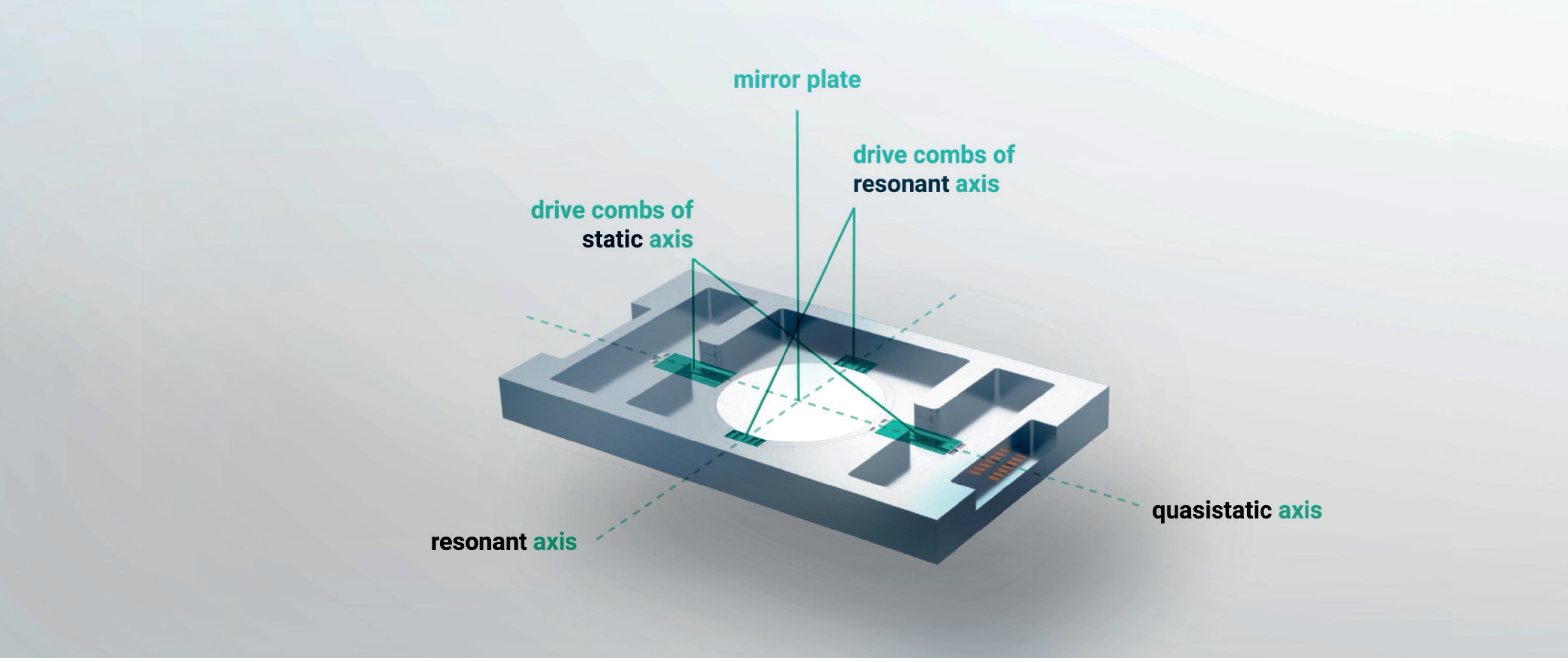
Specifics of resonant microscanner mirrors

The mirror plate of the microscanners is excited to resonant oscillation by electrostatic, planar comb drives. The oscillation amplitude is set by adjusting the drive voltage or frequency. In 2D microscanners, the mirror is suspended on a gimbal. The frequency of the two oscillations is set independently of each other in the design. Each of the two axes is excited individually so that the amplitude of each oscillation can be set and controlled independently of the other.

Resonant scanner mirrors are most efficiently operated with a square wave voltage, which can be provided by a commercially available function generator, amplified if necessary. Alternatively, we can offer you the appropriate electronics – including trigger generation and amplitude control.



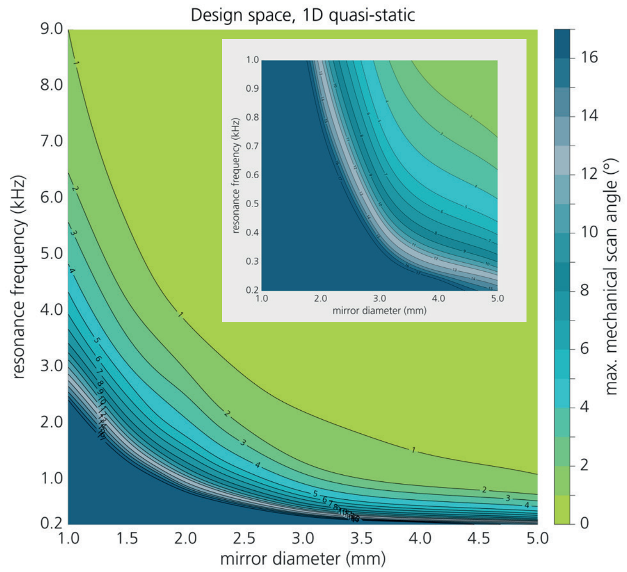
Typical frequency-deflection characteristics of resonant scanner mirrors



Setup of a Linscan microscanner with second resonant axis

Design spaces for 1D quasi-static MEMS scanners

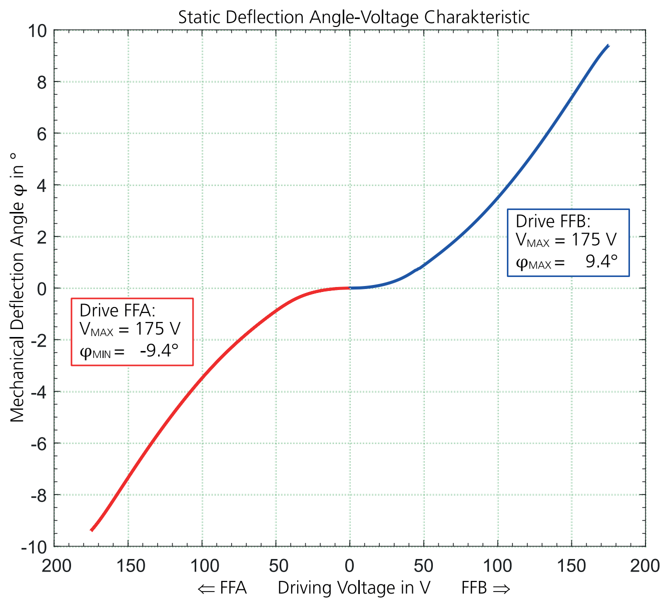
Non-resonant or quasi-static microscanners are designed for arbitrary trajectories, e.g., with triangular, serrated, or stepwise shape. The natural frequency is a very important parameter also for quasi-static MEMS scanners. In contrast to resonantly oscillating scanners, which are operated close to their natural frequency, quasi-static scanning should be significantly below the natural frequency. This prevents undesired overshoot. The settling time for the addressed target position is kept short. It is possible to control or regulate any given scan trajectories with high accuracy.



Specifics of non-resonant microscanners

Non-resonant microscanners are equipped with electrostatically operated out-of-plane vertical comb drives. It is possible to combine a non-resonant frame axis with a resonant mirror axis within one monolithic device.

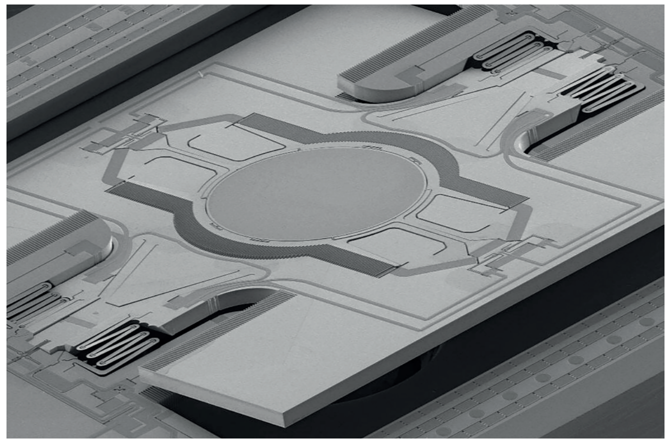
All mechanical components are created as two-dimensional structures in a layer of monocrystalline silicon. The out-of-plane vertical comb electrodes are elevated out of the device plane by an adhesive wafer bonding process. A second silicon wafer with convex structures is bonded on the surface of the structured device layer, displacing a part of the vertical comb electrodes. By this a very precise alignment of the electrodes to each other is achieved.



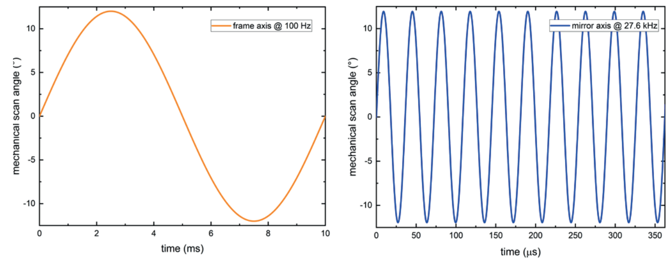
Typical static voltage deflection characteristic of a quasi-static scanner

Gimbal 2D MEMS scanners

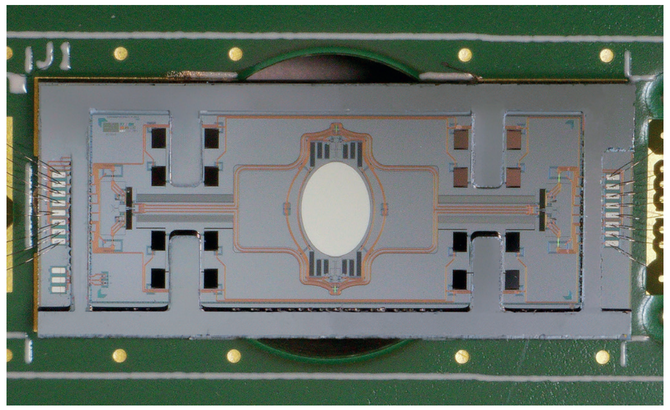
The 1D MEMS scanners described above can be combined on the chip with gimbal suspension, i.e., mechanically independent axes, to create 2D scanners. Two options are available: The combination of a quasi-static frame axis with a resonant inner mirror axis or two resonantly oscillating axes. The effect on the 2D scan trajectory for the combination options is shown as an example in the following images. In double-resonant scanners, a slow resonant axis is combined with a fast resonant axis. A slow quasi-static axis in combination with a fast resonant axis result in a quasi-static resonant scanner.



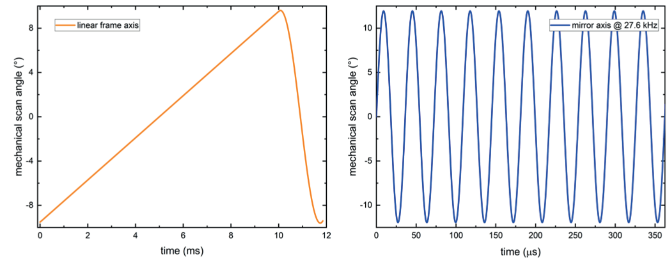
MEMS scanner 2D resonant: frame frequency 100 Hz, mirror frequency 27,600 Hz



Sinusoidal trajectories of the slow (left) and fast (right) resonant axis



MEMS scanner 2D quasi-static / resonant: frame frequency 170 Hz, mirror frequency 4,500 Hz

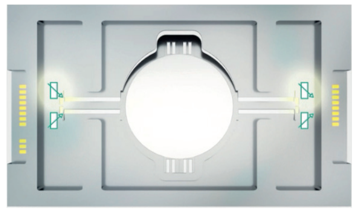


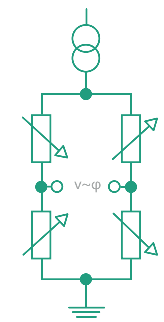
Typical linearized trajectory of the non-resonant axis (left) and sinusoidal trajectory of the resonant axis (right)

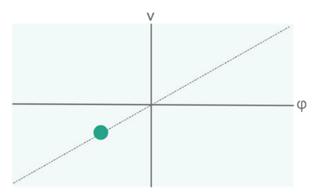
Monolithically integrated piezoresistive position sensing

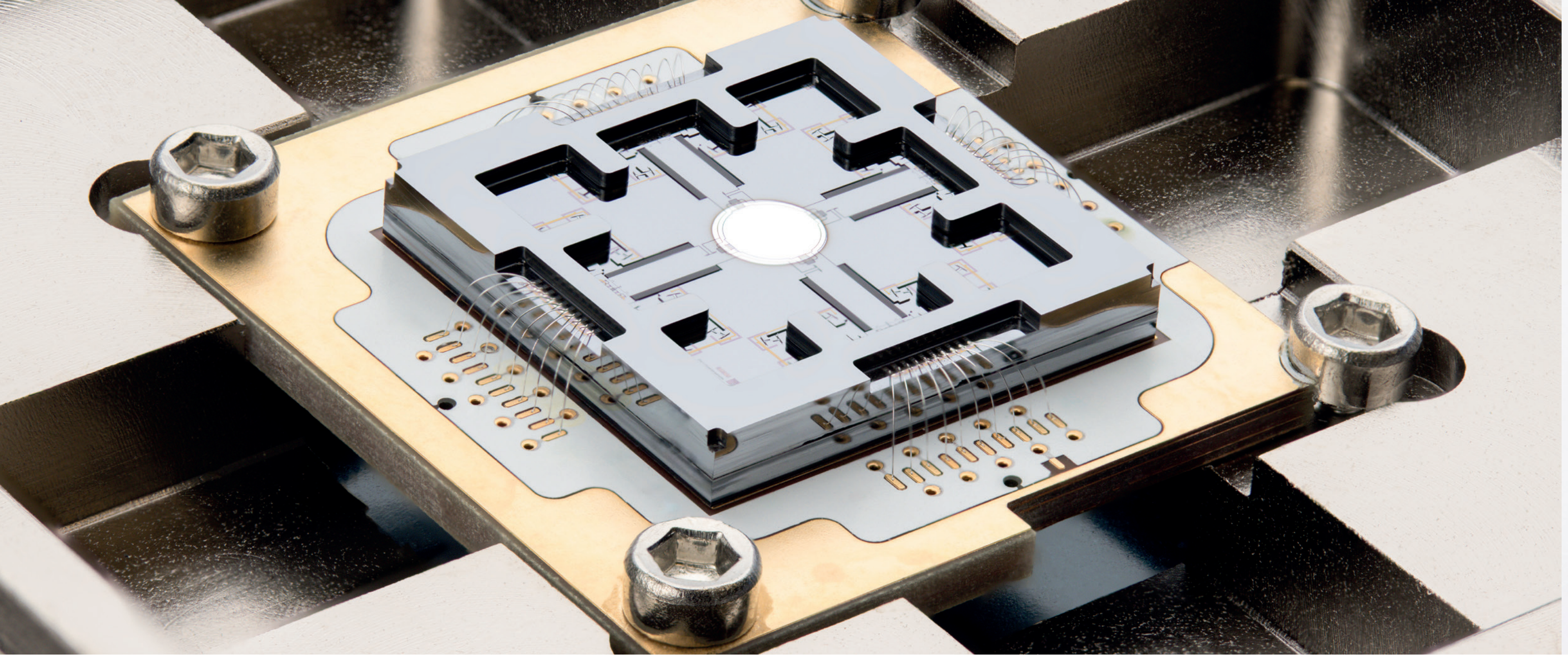
At all 1D and 2D MEMS scanners piezoresistive deflection sensing for each torsional axis is monolithically integrated on the chip. Four resistors sensitive to the mechanical stress are placed next to the torsion springs. The read-out circuit is similar to a Wheatstone bridge. Hence, the deflection sensitivity is increased compared to a single resistor. Sensitivity to temperature changes is suppressed. The mechanical deflections of the mirror and frame axis can be measured continuously.

Monolithic integrated position sensing





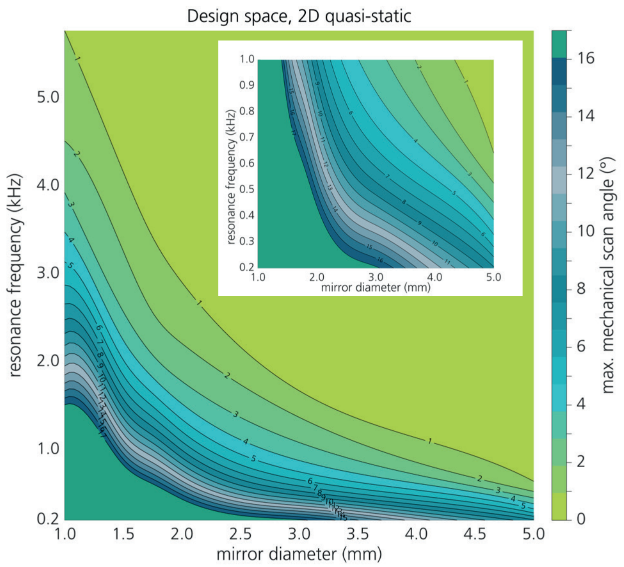




biaxial non-resonant vector scanner with electrostatic actuation

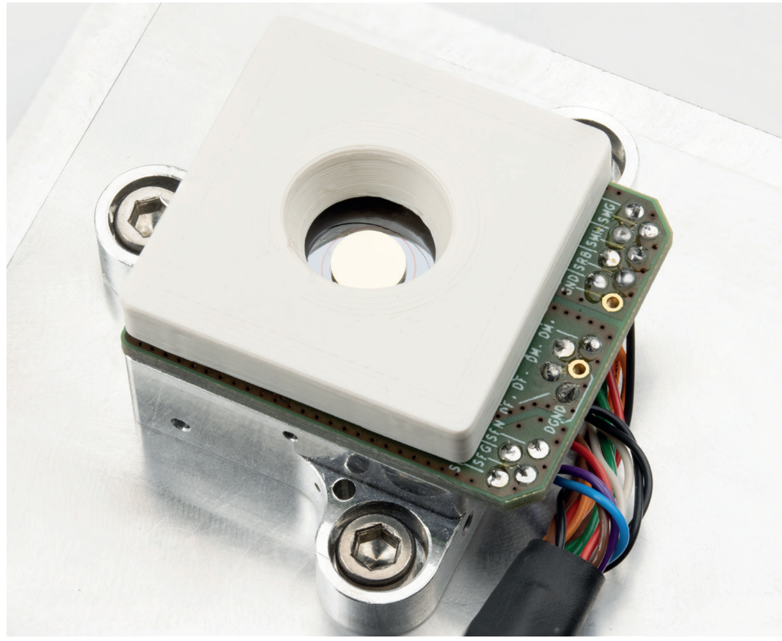
2D vector scanners (non-gimballed)

New in the family of IPMS MEMS microscanners are non-gimballed vectorial 2D scanners with integrated deflection sensors. The design spaces shown here have been created on the basis of two design points that have already been realized. These specify the ranges for deflection, natural frequency and mirror diameter within customized scanner designs can be definitively created and manufactured. Further parameter combinations beyond the design space shown here are also possible. However, the feasibility of such designs must then be assessed as part of a feasibility study.

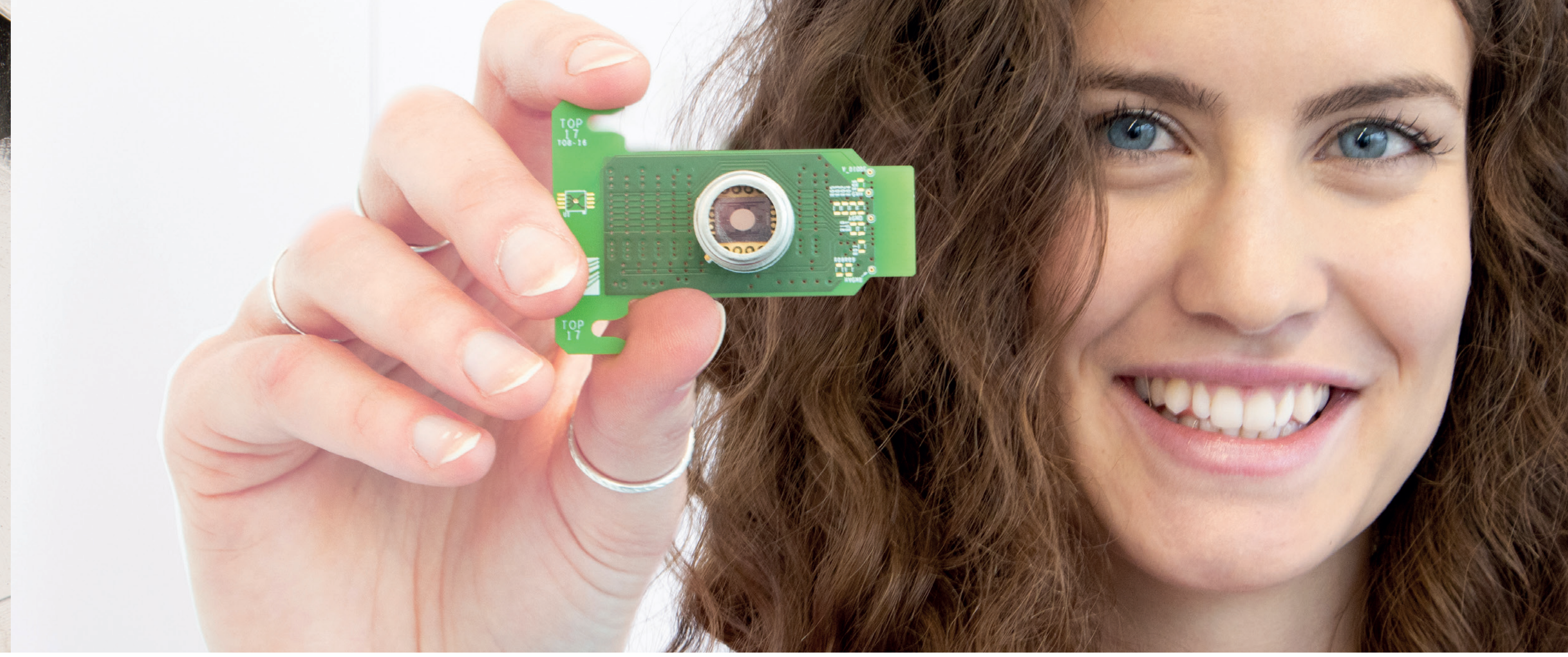


Electro-magnetic 2D vector scanners (gimballed)

The MEMS design space is further expanded by gimballed 2D vector scanners with electro-magnetic actuation. Electromagnetic drives allow higher forces and therefore larger mirror plates and operating speeds. For this type of drive, miniature magnets are applied to the MEMS structure. A detailed presentation can be found in our data sheet »2D vector scanning module I2DQSEM01 with electromagnetic drive«.



biaxial non-resonant vector scanner with electrostatic actuation



Evaluation kits

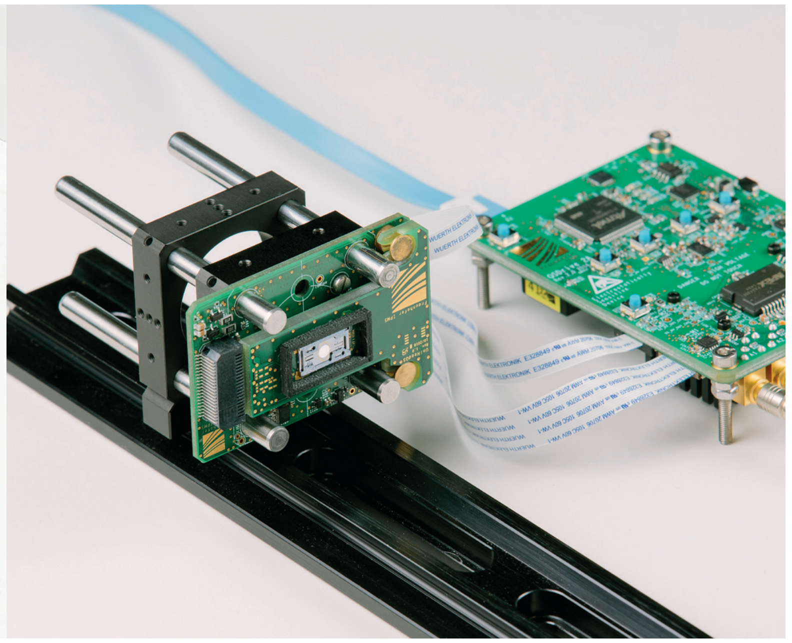
Fraunhofer IPMS offers various evaluation kits to operate MEMS scanner devices conveniently and in accordance with specifications without having to develop own control electronics. All that is additionally required is a power supply and a computer on which the control software can run.

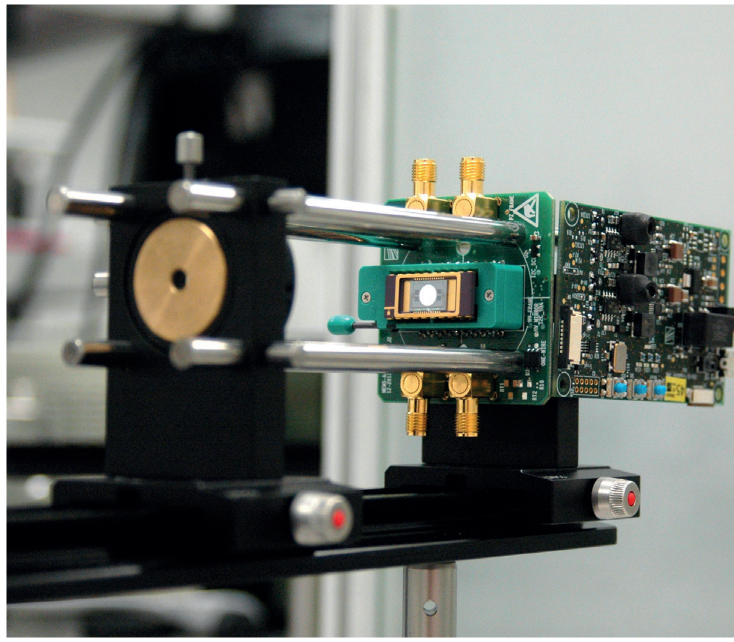
QSDrive scan kit for quasi-static / resonant MEMS

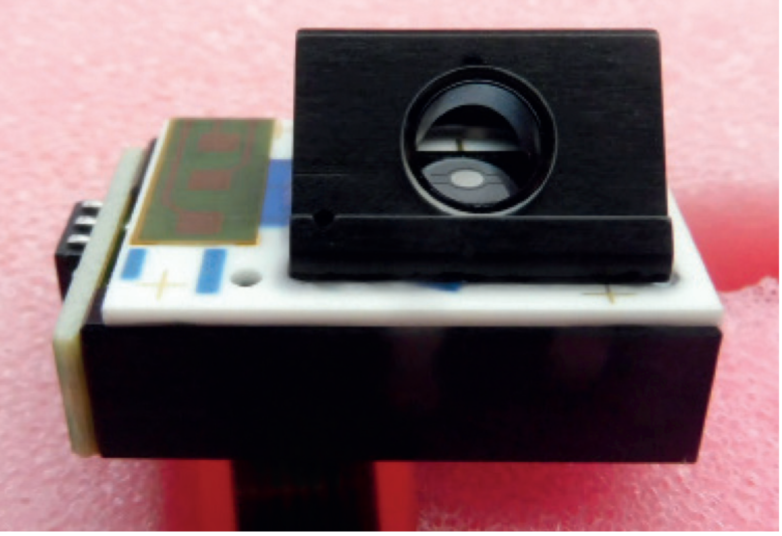
The »QSDrive Scan Kit« evaluation kit consists of a ResoLin device – a gimbal MEMS scanner with a linear axis and an optional, orthogonally oriented resonant axis – as well as control electronics. The device is held by a scan head, which can be easily integrated into standard optical test setups. Controlled operation of the non-resonant axis enables optimized trajectories with minimized deviation from the target trajectory and operation of the resonant axis with amplitude control. The function is controlled by software that communicates with the electronics via USB.

SiMeDri for resonant MEMS scanners

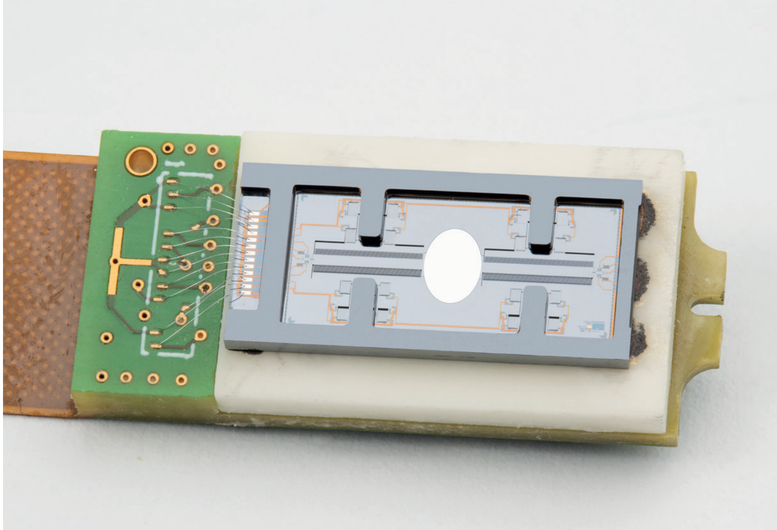
The SiMeDri evaluation kit comprises a resonant 1D or 2D microscanner mirror and an electronic drive unit. The driver provides all signals to operate two resonant axes. Signals of the deflection sensors are acquired. The oscillation amplitude can be controlled. It consists of a driver board and a MEMS board that can be plugged together directly.







Scan module with 1D resonant Fraunhofer IPMS scanner, used in the light sheet microscope ZEISS Lightsheet 7



Quasi-static scanner in a module for head-mounted displays

Applications of MEMS microscanners

- Image acquisition, e.g. for technical and medical endoscopes
- Optical coherence tomography (OCT)
- Microscopy (fluorescence, confocal etc.)
- Object measurement / triangulation
- 3D cameras, LIDAR
- Object recognition / 1D and 2D light curtains
- Spectroscopy, scanning gratings, FTIR
- wavelength tunable lasers (e.g., QCL)
- Laser wavelength modulation
- Laser marking and processing of materials
- Laser projection / display as head-mounted display (HMD), head-up display (HUD), augmented and virtual reality (AR, VR)
- Linear scanning
- Beam positioning / trajectory tracking
- Optical vibration compensation, e.g., hand-held laser
- Medical / laser therapeutic applications (ophthalmology, dermatology …)
- Barcode / QR code reading

Excellent mechanical and optical properties

All mechanically stressed elements are defined in a single-crystal silicon functional layer and fabricated on a BSOI substrate in a bulk micromechanical manufacturing process. This material is characterized by excellent elastic and fracture mechanical properties. In particular, no fatigue phenomena occur during operation due to its single crystallinity. The standard manufacturing process and the design process accompanied by FEM simulations guarantee the following properties:

- Wide design versatility
- Superior dynamics due to minimal moving masses
- High mechanical stability (shock resistance > 2500 g)
- No fatigue mechanism, single crystalline silicon substrate
- Operation at atmospheric ambient, vacuum packages possible
- Different coating options
- High substrate flatness / static planarity (radius of curve > 10 m, optional > 50 m)
- Low dynamic distortion (typically better than λ/20)
- Low power consumption
- Large temperature range (-40°C – 110°C, automotive spec, higher optional)
- Scalable/high volume production ready

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