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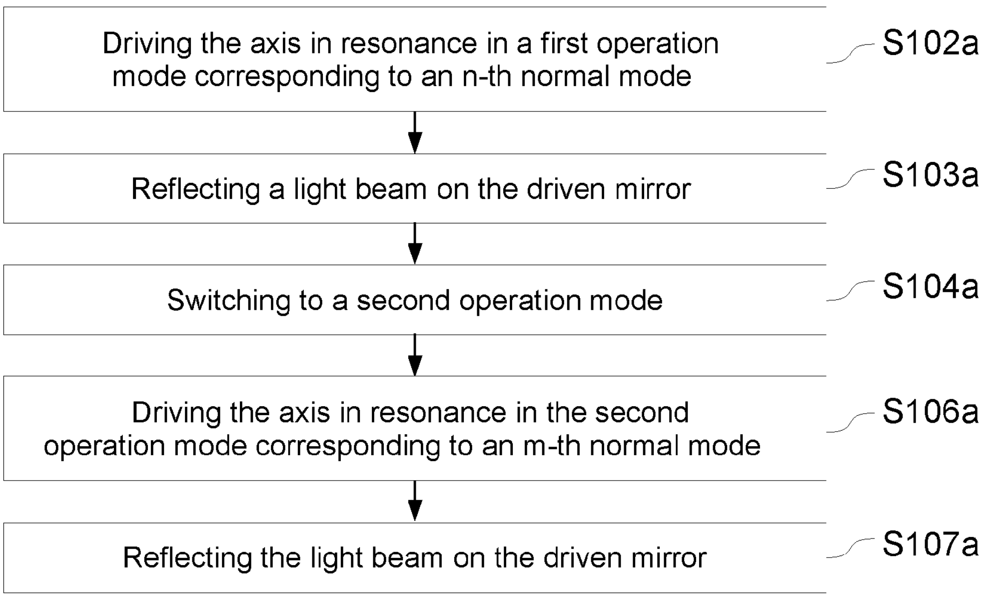
(54) **METHOD AND APPARATUS FOR OPERATING A MICROMIRROR**

(57) The present disclosure relates to methods and apparatuses for operating a micromirror device 10 which comprises a mirror (300) configured to be driven to oscillate about at least one axis. This involves selecting an operation mode among at least two operation modes of the micromirror device 10, wherein a first operation mode is associated with oscillation of the mirror 300 substantially at a resonance frequency of an N-th transverse normal mode of oscillation of the mirror 300 with respect to the axis A1, and a second operation mode of the at least two operation modes is associated with oscillation of the mirror 300 substantially at a resonance frequency of another M-th transverse normal mode of oscillation of the mirror 300 with respect to the axis A1.

Fig. 13



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Description

[0001] The present disclosure relates to a method and apparatus for operating a micromirror, in particular a micromirror device for 1D scanning and/or 2D scanning, 2D projection and/or interferometry applications. In particular, the present disclosure relates to methods and apparatuses for operating a 1D or 2D-micromirror, such as, for example, a 1D or 2D-MEMS-micromirror.

Background

[0002] In the prior art, micromirror devices, e.g., based on MEMS (microelectromechanical systems) technology, are described for use in different applications, including 1D and/or 2D scanning applications, 2D projection applications, and/or interferometry applications.

[0003] For example, the non-patent literature article "2D Scanning Micromirror with Large Scan Angle and Monolithically Integrated Angle Sensors Based on Piezoelectric Thin Film Aluminum Nitride" by authors K. Meinel et al, November 18, 2020, Sensors 2020, Vol. 20, 6599, describes resonant-operated piezoelectrically-driven 2D-micromirror devices for use in applications for LIDAR scanners or laser scanner projectors. Herein, a MEMS mirror is operable to be driven to oscillate about two axes, i.e. in two dimensions (2D), so as to deflect an incoming laser on the oscillating mirror according to a so-called Lissajous-pattern. The oscillations in both axes are driven to operate at the respective resonant frequencies so as to achieve large tilt angles with high energy efficiency.

[0004] Other resonant-operated 2D micromirrors are known, for example, from: non-patent literature article "AlScN Piezoelectric MEMS Mirrors with Large Field of View for LiDAR Application" by authors Y. Liu et al, September 18, 2022, Micromachines 2022, Vol. 13, 1550, describing resonant-operated piezoelectrically-driven 2D-micromirror devices for use in LIDAR scanning applications, and the doctoral thesis paper "Entwicklung, Herstellung und Charakterisierung piezoelektrischer Mikrospiegel" (engl.: Development, Manufacture and Characterization of Piezoelectric Micromirrors) by author S. Gu-Stoppel, 2016, Books on Demand, Norderstedt, ISBN: 9783739239583, describes relevant background information on development and manufacturing of piezoelectrically-driven 1D- or 2D-micromirror devices for different applications such as laser image projection.

[0005] Document US 2020/0386985 A1 also describes piezoelectrically-driven 2D-micromirror devices for different applications such as LIDAR scanning.

[0006] In the prior art, it is known to operate 2D-micromirrors in a so-called raster pattern for scanning or projection applications, in which the laser is deflected according to a raster pattern, see e.g. Fig. 1, in which one axis is operated in a fast resonant oscillation operation and the other axis is operated comparatively slowly at frequencies much lower than the respective resonance frequency of the other axis, referred to as quasi-static operation. However, one drawback of such quasi-static operation is that comparatively high energies are required to achieve sufficiently high tilt angles of the mirror about the quasi-static axis so that the device cannot be operated efficiently as desired.

[0007] In view of such drawback, it can be preferred to operate such 2D-micromirrors in resonant operation in both axes, in which the oscillation about each respective axis is driven to oscillate substantially at (or at least very close to) the respective resonant frequency of the respective axis. This typically leads to so-called Lissajous scan or projection patterns; see, e.g., the exemplary Lissajous patterns of Figs. 2A to 3B.

[0008] In some preferred applications, the micromirror MEMS design structure can be designed such that the resonance frequencies of the two axes are substantially similar, leading to Lissajous patterns such as exemplarily shown in Figs. 2A and 2B.

[0009] For example, the Lissajous patterns of Figs. 2A and 2B have been exemplarily created by the online tool https://academo.org/demos/lissajous-curves/, and the ratio of resonance frequencies in the Lissajous pattern of Fig. 2A is exemplarily selected as 9:10 and the ratio of resonance frequencies in the Lissajous pattern of Fig. 2B is exemplarily selected as 19:20. With the typical higher frequencies of operation of micromirror devices, the resonance frequency ratio can be selected to be substantially 1:1 in some examples.

[0010] However, for projection applications, it can be recognized that some users (typically about 50% of users) exhibit subjective subconscious user preferences in favor of images that are projected rather according to a more raster-like patterns compared to a Lissajous pattern with substantially similar resonance frequencies in both axes as exemplarily shown in Figs. 2A or 2B.

[0011] For such type of users and their subjective subconscious user preferences, it is typically required to provide a different product in which the MEMS structure is designed such that the resonance frequency of the first axis is significantly or at least comparatively larger than the resonance frequency of the second axis, leading to Lissajous patterns that are more "raster-like" such as the Lissajous patterns exemplarily shown in Figs. 3A or 3B.

[0012] For example, the Lissajous patterns of Figs. 3A and 3B have been exemplarily created by the online tool https://academo.org/demos/lissajous-curves/, and the ratio of resonance frequencies in the Lissajous pattern of Fig. 3A is exemplarily selected as 1:9 and the ratio of resonance frequencies in the Lissajous pattern of Fig. 3B is exemplarily selected as 1:20.

[0013] Accordingly, regarding the operation of micromirror devices for image projection applications, one group of the users may have better subjective experiences with images projected by using a projection pattern that rather resembles a more raster-like pattern (such as Fig. 1 or the Lissajous patterns according to Figs. 3A and 3B), while the other group of users may have better subjective experiences with images projected by using a projection pattern that rather resembles a more homogenous pattern (such as the Lissajous patterns according to Figs. 2A and 2B).

[0014] Also, for other imaging applications, or for projecting images at different aspect ratios (e.g. 4:3, 16:9 or 21:9, etc.), and/or for projecting images at different image resolutions, users may prefer one type of projection pattern over the other or vice versa.

[0015] Still, it is preferred to avoid use of raster patterns by operation of one of the axes, since this leads to significantly reduced energy efficiency. Hence, it is preferred to provide micromirrors that can be operated in both axes at the respective resonance frequencies.

[0016] However, while it is possible to provide efficient MEMS micromirror devices that can be resonant-operated in both axes very efficiently at a selected tuned ratio of resonance frequencies of the two axes, there is yet another drawback that different micromirror MEMS devices tuned to different resonant frequency ratios would need to be provided for the market so that different groups of users can be provided with the respective product coping with their subjective user preferences.

[0017] More generally, in some exemplary aspects, it may be desirable to provide a single micromirror device and enabling efficiently operating the micromirror device preferably such that different efficient modes of operation can be provided, potentially including being suitable for different applications and/or application functions, such as 1D and/or 2D scanning, 2D projection, and/or interferometry applications.

[0018] In view of the above, it is an object of the present disclosure to provide a method and apparatus for operating a micromirror preferably avoiding the above drawbacks and/or at least improving on the above drawbacks and/or enabling efficiently operating a micromirror device preferably such that different efficient modes of operation can be provided, potentially including being suitable for different applications and/or application functions.

Summary

[0019] For solving the above object, there is proposed a method for operating a micromirror device according to claim 1. Furthermore, an apparatus for operating a micromirror device and a corresponding computer program product, e.g. including firmware of a controller, according to the other independent claims are proposed. Dependent claims relate to some exemplary embodiments. According to a first aspect, there is proposed a method for operating a micromirror device. According to a second aspect, there is proposed a controller for operating the micromirror device and/or an apparatus comprising such controller and the micromirror device. According to a third aspect, there is proposed a computer program product to cause a controller to execute the method for operating the micromirror device.

[0020] In some exemplary aspects, the micromirror device may comprise a mirror configured to be driven to oscillate with respect to one or more axes, preferably including tilt oscillations about at least one axis, for example, for scanning applications and/or for projection applications, and/or including shift oscillations, for example, interferometry applications. In some exemplary aspects, the mirror may be held by a structured device layer of a MEMS structure, wherein the structured device layer may include springs to hold the mirror within a frame of the MEMS structure. In some exemplary aspects, the mirror can be configured to be driven to oscillate in two dimensions with respect to two axes (2D), for example, for scanning applications and/or for projection applications. The micromirror device may include actuators for driving the oscillation of the mirror with respect to the one or more axes.

[0021] According to some exemplary aspects, operating a micromirror device may comprise selecting an operation mode among at least two operation modes of the micromirror device, in particular at least two selectable operation modes of the micromirror device.

[0022] According to some exemplary aspects, a first operation mode of the at least two operation modes can be associated with oscillation of the mirror of the micromirror device, preferably with respect to a first axis, and/or preferably substantially at a resonance frequency of an N-th transverse normal mode of oscillation of the mirror associated with the first axis.

[0023] According to some exemplary aspects, a second operation mode of the at least two operation modes can be associated with oscillation of the mirror of the micromirror device, preferably with respect to the first axis, and/or preferably substantially at a resonance frequency of another M-th transverse normal mode of oscillation of the mirror associated with the first axis.

[0024] According to some exemplary aspects, the selectable operation modes may include two or more operation modes, wherein each selectable operation mode is preferably associated with oscillation of the mirror of the micromirror device, preferably with respect to the first axis, and/or preferably substantially at a respective resonance frequency of a respective transverse normal mode of oscillation of the mirror associated with the first axis.

[0025] According to some exemplary aspects, it is preferred that M and N are different, wherein transverse normal modes of oscillation associated with a respective certain axis are numbered by positive integers, such that N = 1, 2, 3, 4, 5, 6, ... or higher and M = 1, 2, 3, 4, 5, 6, ... or higher, preferably with N ≠ M.

[0026] According to some exemplary aspects, operating a micromirror device may comprise driving the oscillation of the mirror according to the selected operation mode.

[0027] According to some exemplary aspects, operating a micromirror device may comprise driving, when the first operation mode is selected, the oscillation of the mirror according to the selected first operation mode substantially at the resonance frequency associated with the N-th transverse normal mode of oscillation of the mirror associated with the first axis (e.g. oscillations about a second axis).

[0028] According to some exemplary aspects, operating a micromirror device may comprise driving, when the second operation mode is selected, the oscillation of the mirror according to the selected second operation mode substantially at the resonance frequency associated with the M-th transverse normal mode of oscillation of the mirror associated with the first axis (e.g. oscillations about a second axis).

[0029] According to some exemplary aspects, the respective transverse normal mode of the selected operation mode (first and/or second operation mode) can be an even-numbered transverse normal mode associated with the first axis. Preferably, the oscillation of the mirror can then be driven according to the selected operation mode for performing a projection and/or scanning operation of the micromirror device, preferably utilizing a light beam being reflected on the oscillating mirror.

[0030] According to some exemplary aspects, the respective transverse normal mode of the selected operation mode (first and/or second operation mode) can be an odd-numbered transverse normal mode associated with the first axis. Preferably, the oscillation of the mirror can then be driven according to the selected operation mode for performing an interferometry operation of the micromirror device, preferably utilizing a light beam being reflected on the oscillating mirror.

[0031] According to some exemplary aspects, the N-th transverse normal mode and the M-th transverse normal mode are different even-numbered transverse normal modes of oscillation of the mirror. Accordingly, it is preferred that M and N are different even numbered positive integers, wherein transverse normal modes of oscillation are numbered by positive integers, such that N = 2, 4, 6, 8, ... or higher and M = 2, 4, 6, 8, ... or higher, with N ≠ M. This allows switching between different scanning/projection applications using different resonance frequencies.

[0032] According to some exemplary aspects, N = 2 and M = 4, 6 or 8 (or vice versa).

[0033] According to some exemplary aspects, the N-th transverse normal mode and the M-th transverse normal mode are different odd-numbered transverse normal modes of oscillation of the mirror. Accordingly, it is preferred that M and N are different odd numbered positive integers, wherein transverse normal modes of oscillation are numbered by positive integers, such that N = 1, 3, 5, 7, ... or higher and M = 1, 3, 5, 7, ... or higher, with N ≠ M. This allows switching between different interferometry applications using different resonance frequencies.

[0034] According to some exemplary aspects, the N-th transverse normal mode can be an even-numbered transverse normal modes of oscillation of the mirror and the M-th transverse normal mode can be an odd-numbered transverse normal mode of oscillation of the mirror. This allows switching between projection/scanning applications and interferometry applications.

[0035] According to some exemplary aspects, the operation modes of the micromirror device may include further one or more operation modes including at least a third operation mode associated with oscillation of the mirror about the at least one axis substantially at a third resonance frequency of another K-th normal mode of oscillation of the mirror with K being different from each of M and N.

[0036] According to some exemplary aspects, operating a micromirror device may comprise switching from the first operation mode to the second operation mode, wherein preferably selecting the operation mode comprises switching from the first operation mode to the second operation mode.

[0037] According to some exemplary aspects, operating a micromirror device may comprise switching from the second operation mode to the first operation mode, wherein preferably selecting the operation mode comprises switching from the second operation mode to the first operation mode.

[0038] That is, according to some exemplary aspects, selecting the operation mode comprises switching between the first operation mode and the second operation mode.

[0039] According to some exemplary aspects, the respective transverse normal modes of the first and second operation modes can be different even-numbered transverse normal modes associated with the first axis, and switching between the first operation mode and the second operation mode can preferably switch between two operation modes for performing resonant-operated projection or scanning operations of the micromirror device at different respective resonant frequencies associated with the first axis.

[0040] According to some exemplary aspects, the respective transverse normal modes of the first and second operation modes can be different odd-numbered transverse normal modes associated with the first axis, and switching between the first operation mode and the second operation mode can preferably switch between two operation modes for performing resonant-operated interferometry operations of the micromirror device at different respective resonant frequencies associated with the first axis.

[0041] According to some exemplary aspects, the respective transverse normal mode of the first operation mode can be an even-numbered transverse normal mode, and/or the respective transverse normal mode of the second operation mode can be an odd-numbered transverse normal mode (or vice versa), and switching between the first operation mode and the second operation mode can preferably switch between an operation mode for performing a resonant-operated projection or scanning operation of the micromirror device and an operation mode for performing a resonant-operated interferometry operation of the micromirror device.

[0042] According to some particularly preferable exemplary aspects, the mirror is configured to be driven to oscillate in two dimensions, preferably with respect to the first axis and another second axis, for example, about the first axis and/or about the second axis, e.g., preferably in two dimensions, for example, to preferably enable generating 2-dimensional projection or scan patterns, e.g. by reflecting a light beam on the oscillating mirror.

[0043] According to some exemplary aspects, operating a micromirror device may comprise driving the oscillation of the mirror according to the selected operation mode, including driving a substantially resonant oscillation of the mirror with respect to the first axis and driving a substantially resonant oscillation of the mirror with respect to the second axis.

[0044] According to some exemplary aspects, the first operation mode can be associated with oscillation of the mirror about the second axis substantially at the resonance frequency of the N-th transverse normal mode of oscillation of the mirror.

[0045] According to some exemplary aspects, the first operation mode can be associated with a tilt oscillation of the mirror about the second axis preferably driven substantially at the resonance frequency of an even-numbered N-th transverse normal mode of oscillation of the mirror with respect to the first axis.

[0046] According to some exemplary aspects, the second operation mode can be associated with oscillation of the mirror about the second axis substantially at the resonance frequency of the M-th normal mode of oscillation of the mirror.

[0047] According to some exemplary aspects, the second operation mode can be associated with a tilt oscillation of the mirror about the second axis preferably driven substantially at the resonance frequency of another even-numbered M-th normal mode of oscillation of the mirror with respect to the first axis.

[0048] According to some exemplary aspects, operating the micromirror device may further comprise driving the oscillation of the mirror about the first axis substantially at a resonance frequency of oscillation of the mirror about the first axis, preferably while driving the oscillation of the mirror about the second axis according to the selected operation mode, preferably to generate a 2-dimensional projection or scan pattern, e.g. by reflecting a light beam on the oscillating mirror.

[0049] According to some exemplary aspects, operating the micromirror device may further comprise generating a Lissajous scan or projection pattern by reflecting a light beam on the mirror, preferably while driving the oscillation of the mirror about the first axis substantially at a resonance frequency of oscillation of the mirror about the first axis and/or driving the oscillation of the mirror about the second axis according to the selected operation mode.

[0050] According to some exemplary aspects, a first type of Lissajous pattern is generated in the first operation mode and/or a second type of Lissajous pattern is generated in the second operation mode.

[0051] According to some exemplary aspects, in particular in the second operation mode, a first ratio between the resonance frequency of oscillation of the mirror about the first axis and the respective resonance frequency of the N-th normal mode of oscillation of the mirror about the second axis according to the first operation mode is substantially equal or larger than 1: 1.2 and/or substantially equal or smaller than 1: 0.8, in particular substantially equal or larger than 1 : 1.1 and/or substantially equal or smaller than 1: 0.9, and preferably the first ratio is substantially 1:1.

[0052] According to some exemplary aspects, in particular in the second operation mode, a second ratio between the resonance frequency of oscillation of the mirror about the first axis and the respective resonance frequency of the M-th normal mode of oscillation of the mirror about the second axis according to the second operation mode is substantially equal or smaller than 1:2, in particular substantially equal or smaller than 1: 3 and preferably the second ratio is substantially equal or smaller than 1: 5; and/or the second ratio is substantially equal or larger than 1: 20 and preferably the second ratio is substantially equal or larger than 1:10.

[0053] According to some exemplary aspects, operating the micromirror device may further comprise driving the oscillation of the mirror about the second axis according to the first operation mode substantially at the resonance frequency of the N-th normal mode of oscillation of the mirror about the second axis and/or driving the oscillation of the mirror about the second axis according to the second operation mode substantially at the resonance frequency of the M-th normal mode of oscillation of the mirror about the second axis.

[0054] According to some exemplary aspects, driving the oscillation of the mirror about the first axis according to the first operation mode and/or driving the oscillation of the mirror about the first axis according to the second operation mode is performed substantially at the same resonance frequency of a transverse normal mode of oscillation of the mirror about the first axis and/or with respect to the second axis.

[0055] According to some exemplary aspects, driving the oscillation of the mirror about the first axis according to the first operation mode and second operation mode can include operating the oscillation of the mirror about the first axis according to the first operation mode and second operation mode in different normal modes of the first axis.

[0056] For example, driving the oscillation of the mirror about the first axis according to the first operation mode and driving the oscillation of the mirror about the first axis according to the second operation mode can be performed substantially at different resonance frequencies of different even-numbered transverse normal mode of oscillation of the mirror about the first axis and/or with respect to the second axis.

[0057] For example, driving the oscillation of the mirror about the first axis according to the first operation mode can be operated substantially at a resonance frequency of a J-th normal mode of oscillation of the mirror about the first axis and the second oscillation mode can be operated substantially at a resonance frequency of an L-th normal mode of oscillation of the mirror about the first axis, J being different from L, J and L being preferably even-numbered positive integers.

[0058] While certain exemplary aspects have been described above, it is to be understood that such exemplary aspects and features thereof are merely illustrative of (and are not to be understood restrictive on) the broad disclosure, and that the exemplary aspects are not limited to the specific constructions and arrangements shown and described above or below, since various other changes, combinations, omissions, modifications and substitutions, in addition to those set forth in the above or below description, are possible. Those skilled in the art will appreciate that various adaptations, modifications, and/or combination of the just described aspects can be configured or be provided. Therefore, it is to be understood that further aspects may be practiced other than as specifically described herein. For example, unless expressly stated otherwise, the steps of processes described herein may be performed in orders different from those described herein and one or more steps may be combined, split, or performed simultaneously. Those skilled in the art will also appreciate, in view of this disclosure, that different aspects described herein may be combined to form other aspects of the present disclosure.

Brief Description of Drawings

[0059]

Fig. 1 is a schematic illustrative view of an exemplary raster scan or projection pattern;

Fig. 2A is a schematic illustrative view of an exemplary Lissajous scan or projection pattern with similar resonance frequencies in both axes;

Fig. 2B is a schematic illustrative view of another exemplary Lissajous scan or projection pattern with similar resonance frequencies in both axes;

Fig. 3A is a schematic illustrative view of an exemplary Lissajous scan or projection pattern with the resonance frequency of one axis being comparatively smaller than the resonance frequency of the other axis;

Fig. 3B is a schematic illustrative view of another exemplary Lissajous scan or projection pattern with the resonance frequency of one axis being comparatively smaller than the resonance frequency of the other axis;

Fig. 4 is a schematic exemplary illustration of the first to tenth normal modes of oscillation of a beam clamped on both sides (also referred to as double-clamped or clamped-clamped bar vibrations);

Fig. 5 is a schematic exemplary top view of a device layer of an apparatus according to an exemplary embodiment;

Fig. 6 is a schematic exemplary cross-sectional view of the device layer of **Fig. 5** along the axis A1;

Fig. 7 is a schematic exemplary cross-section view of a micromirror device according to an exemplary embodiment;

Fig. 8A is a schematic exemplary cross-sectional view of the exemplary device layer of **Fig. 5** along the axis A1 in a state of exemplary vibration about the axis A2 in the second transverse normal mode of oscillation;

Fig. 8B is a schematic exemplary cross-sectional view of the exemplary device layer of **Fig. 5** along the axis A1 in a state of exemplary vibration about the axis A2 in the fourth transverse normal mode of oscillation;

Fig. 8C is a schematic exemplary cross-sectional view of the exemplary device layer of **Fig. 5** along the axis A1 in a state of exemplary vibration about the axis A2 in the sixth transverse normal mode of oscillation;

Fig. 8D is a schematic exemplary cross-sectional view of the exemplary device layer of **Fig. 5** along the axis A1 in a state of exemplary vibration about the axis A2 in the eighth transverse normal mode of oscillation;

Fig. 9A is a schematic exemplary cross-sectional view of the exemplary device layer of **Fig. 5** along the axis A1 in a state of exemplary vibration in the first transverse normal mode of oscillation;

Fig. 9B is a schematic exemplary cross-sectional view of the exemplary device layer of **Fig. 5** along the axis A1 in a state of exemplary vibration in the third transverse normal mode of oscillation;

Fig. 9C is a schematic exemplary cross-sectional view of the exemplary device layer of **Fig. 5** along the axis A1 in a state of exemplary vibration in the fifth transverse normal mode of oscillation;

Fig. 10 is a schematic exemplary view of a curve of amplitude as a function of frequency at an exemplary resonance frequency f_n of an n-th normal mode of oscillation;

Fig. 11 is a schematic functional block diagram of an apparatus according to some exemplary embodiments;

Fig. 12 is a schematic flow chart exemplarily illustrating a method of operating a 2D micromirror according to some exemplary embodiments;

Fig. 13 is a schematic flow chart exemplarily illustrating another method of operating a 2D micromirror according to some further exemplary embodiments;

Fig. 14 is a schematic exemplary top view of another device layer of an apparatus according to some exemplary embodiments;

Fig. 15 is a schematic flow chart exemplarily illustrating another method of operating a 2D micromirror according to some further exemplary embodiments; and

Fig. 16 is a schematic flow chart exemplarily illustrating another method of operating a 2D micromirror according to some further exemplary embodiments.

Detailed Description of the Drawings and Exemplary Embodiments

[0060] In the following, preferred exemplary aspects and exemplary embodiments of the present disclosure will be described in more detail with reference to the accompanying figures. Same or similar features in different drawings and exemplary embodiments are referred to by similar reference numerals. It is to be understood that the detailed description below relating to various preferred exemplary aspects and preferred exemplary embodiments are not to be meant as limiting the scope of the present disclosure.

[0061] **Fig. 1** is a schematic illustrative view of an exemplary raster scan pattern or raster projection pattern and relates to background information. This illustrates exemplarily a raster scan pattern (or raster projection pattern) of a 2D micromirror device (e.g. operated as a scanner or projector) in which one axis is resonant-operated at its respective resonance frequency, whereas the other axis is driven quasi-static at a frequency which is significantly lower than its respective resonance frequency. Quasi-static operation of one axis refers to an operation in which the frequency of the driving signal (i.e. the driven oscillation frequency) is equal or lower than 10% of the resonance frequency associated with the respective axis.

[0062] As mentioned in the background section above, a typical drawback of such raster scan or projection operation of the micromirror is that the quasi-static operation does not easily achieve sufficient tilt angles of the oscillating mirror about the quasi-static axis, and rather high actuation energies are required to achieve sufficient tilt angles. Therefore, quasi-static operation in one of the axes is rather inefficient in terms of energy consumption. Thus, in some exemplary embodiments, it is preferred to avoid quasi-static operation and to rather operate both axes of the 2D micromirror in respective resonant operations at or at least close to the respective resonance frequencies in both of the first and second axes of the micromirror device.

[0063] **Fig. 2A** is a schematic illustrative view of an exemplary Lissajous scan or projection pattern with similar resonance frequencies in both axes. This illustrates exemplarily a Lissajous scan pattern (or Lissajous projection pattern) of a 2D micromirror device (e.g. operated as a scanner or projector) in which both axes are resonant-operated substantially at their respective resonance frequencies, respectively.

[0064] Such uniformly distributed Lissajous pattern can be achieved with both resonance frequencies of the two axes being substantially equal or at least close to each other. For example, the exemplary Lissajous pattern of Fig. 2A has been created with the online tool https://academo.org/demos/lissajous-curves/, and the ratio of resonance frequencies in the Lissajous pattern of Fig. 2A is exemplarily selected as 10:9 (i.e. the difference between the two resonance frequencies of the two axes is about 10%).

[0065] **Fig. 2B** is a schematic illustrative view of another exemplary Lissajous scan or projection pattern with similar resonance frequencies in both axes. For example, the exemplary Lissajous pattern of Fig. 2B has been created with the online tool https://academo.org/demos/lissajous-curves/, and the ratio of resonance frequencies in the Lissajous pattern of Fig. 2B is exemplarily selected as 20:19 (i.e. the difference between the two resonance frequencies of the two axes is about 5%).

[0066] Such uniformly distributed homogenous Lissajous patterns, if desired or preferred, can be achieved with both resonance frequencies of the two axes being substantially equal or at least close to each other (for example with a frequency ratio of about 0.8 to 1.2, or preferably with a frequency ratio of about 0.85 to 1.15, or preferably with a frequency ratio of about 0.9 to 1.1).

[0067] For obtaining higher scanning or projection resolutions, higher frequencies of operation can typically be used in resonant-operated micromirrors, for example, substantially at resonance frequencies equal or more than 1 kHz up to hundreds of kHz, such as up to 200 kHz or more, the resonance frequencies can be selected, e.g., even at substantially the ratio 1:1 in some exemplary embodiments.

[0068] On the other hand, if a different Lissajous pattern such as a more "raster-like" Lissajous pattern may be preferred, it may be preferable to provide a micromirror with tuned resonance frequencies in which the resonance frequency of one axis is comparably smaller than the resonance frequency of the other axis.

[0069] For example, it is possible to tune the design of the micromirror structure such that the resonance frequency of one axis is larger than the resonance frequency of the other axis, e.g., such as by a factor of two or more, or even by a factor of 3 or more, or even higher. For example, the ratio of resonance frequencies of the slow axis and the fast axis can be selected substantially as 1:2 (i.e. the resonance frequency of oscillations about the fast axis is twice the resonance frequency of oscillations about the slow axis), or, in some further exemplary aspects, the ratio of resonance frequencies of the slow axis and the fast axis can be selected substantially as 1:3,1:4,1:5 or lower, such as even 1:10 or lower.

[0070] **Fig. 3A** is a schematic illustrative view of an exemplary Lissajous scan or projection pattern with the resonance frequency of one axis being comparably smaller than the resonance frequency of the other axis. For example, the exemplary Lissajous pattern of Fig. 3A has been created with the online tool https://academo.org/demos/lissajous-curves/, and the ratio of resonance frequencies in the Lissajous pattern of Fig. 3A is exemplarily selected as 1:9.

[0071] **Fig. 3B** is a schematic illustrative view of another exemplary Lissajous scan or projection pattern with the resonance frequency of one axis being comparably smaller than the resonance frequency of the other axis. For example, the exemplary Lissajous pattern of Fig. 3B has been created with the online tool https://academo.org/demos/lissajous-curves/, and the ratio of resonance frequencies in the Lissajous pattern of Fig. 3B is exemplarily selected as 1:20.

[0072] For obtaining higher scanning or projection resolutions, higher frequencies of operation can typically be used in resonant-operated micromirrors, for example, substantially at resonance frequencies equal or more than 1 kHz up to hundreds of kHz, such as up to 200 kHz or more, the resonance frequencies can be selected.

[0073] As mentioned in the background section, for projection applications, it can be recognized that some users (typically about 50% of users) exhibit subjective user preferences in favor of images that are projected rather according to a more raster-like pattern compared to a very homogenously distributed Lissajous pattern with substantially similar resonance frequencies in both axes as exemplarily shown in Figs. 2A or 2B.

[0074] For such users, it is typically preferred to provide a different product in which the micromirror structure is designed such that the resonance frequency of the first axis is tuned to be comparably larger than the resonance frequency of the second axis, leading to then preferred Lissajous patterns that are more "raster-like" such as the Lissajous patterns exemplarily shown in Figs. 3A or 3B.

[0075] However, it remains undesirable to provide different types of products to different user groups, and it can be much more preferable to find a technical solution allowing to provide the ability to project images (or perform scans) in different operation modes with different patterns, e.g. with a first type of Lissajous patterns having substantially equal frequencies in both axes (e.g. such as in Figs. 2A or 2B), and with a second type of Lissajous patterns having a fast axis and a comparatively slower axis, where the frequency of the slower axis is smaller than the frequency of the fast axis, e.g. at a ratio of 1:2 or smaller, such as 1:3, 1:4, 1:5, or smaller, such as even 1:10 or lower, etc.

[0076] Still, it is preferred in some exemplary embodiments that each of the two or more operation modes still operates with both axes being resonant-operated so as to be kept energy efficient, especially compared to the commonly known inefficient quasi-static operation in the slow axis. It was found that this may be advantageously achieved by utilizing different normal modes of vibration (sometimes also referred to as Eigenmodes or natural modes of the oscillation) in at least one of the axes of the respective micromirror design.

[0077] In this connection, the concept of vibrations in different normal modes is exemplarily reviewed with the (traversal) normal modes of the vibrating bar. The so-called Eigenform of vibrations of the vibrating bar describes the standing wave representation of the shape of the vibration. The characteristic equations of the vibrating bar depend on the way the bar is or is not attached or fixed at one or both sides.

[0078] **Fig. 4** is a schematic exemplary illustration of the first to tenth transversal normal modes of oscillation of a vibrating bar clamped on both sides (also referred to as double-clamped or clamped-clamped bar vibrations, used here as an example that is merely of illustrative purposes).

[0079] It is to be noted that, regarding the clamped-clamped bar vibrations of Fig. 4, the odd-numbered transversal normal modes (left-hand column in Fig. 4 with n = 1, 3, 5, etc.) exhibit a transversal shift in the middle position of the bar, whereas the even-numbered transversal normal modes (right-hand column in Fig. 4 with n = 2, 4, 6, etc.) exhibit a stationary nodal point in the middle.

[0080] Accordingly, the even-numbered transversal normal modes have the characteristics that the middle position of the bar does not exhibit traversal oscillation movements, and the middle portion of the bar rather performs an oscillating tilt movement about the stationary middle (nodal) point of the bar. This is true for the clamped-clamped example as well as for all the other vibrating bar scenarios with clamped, free or hinged end on one side and clamped, free or hinged end on the other side, as discussed in various textbooks on the physics of mechanical vibrations.

[0081] Hence, regarding a respective axis of the oscillating system, even-numbered transverse normal modes of vibration in the system provide suitable oscillation modes for scanning or projection patterns, in which the oscillating pattern has a centrally positioned mirror that performs an oscillating tilt movement about the respective axis. Accordingly, even-numbered transverse normal modes of vibration are suitable for scanning and/or projection applications. On the other hand, also odd-numbered transverse normal modes, in which the mirror performs a transverse oscillating shift movement, can be used efficiently for suitable applications, such as e.g. in interferometry applications.

[0082] It is also to be noted that the characterization of even-numbered transverse normal modes as used in the present disclosure refers to the convention of numbering normal modes in which the base oscillation mode is numbered with the number 1, i.e. n = 1 in Fig. 4, wherein another terminology (not used in the present disclosure) may refer to the second normal mode with n = 2 in Fig. 4 as first overtone harmonic mode, i.e. the term "even-numbered normal modes" as used in the present disclosure may, according to another terminology be understood as odd-numbered overtone oscillation modes. In the following numbering of modes will follow the convention of numbering of normal modes (not numbering of overtones).

[0083] Furthermore, the present disclosure will adopt the following numbering paradigm for transverse normal modes: For 1D micromirror devices, in which a mirror can be driven to oscillate with respect to a certain single axis (1D), e.g. for the application of bar code scanning and/or interferometry applications, the normal mode numbers refer to the transverse normal modes in which the mirror oscillates transverse with respect to the single axis. That is, potential other modes, e.g. modes including longitudinal oscillations, are neglected (i.e. not included in the numbering).

[0084] For 2D micromirror devices, in which a mirror can be driven to oscillate with respect to each of two axes independently and/or simultaneously, such as for 2D scanning and/or projection applications or interferometry applications, transverse normal modes are numbered separately with respect to each axis.

[0085] Also, for 2D micromirror devices, the numbering only addresses transverse normal modes, in which the mirror oscillates orthogonally with respect to the plane of the two axes, and other modes, such as parasitic modes and/or modes including longitudinal oscillations (i.e. oscillations in a direction within the plane spanned by the two axes), are neglected (i.e. not included in the numbering).

[0086] It is to be further noted that all of the normal modes, e.g. the normal modes in Fig. 4, represent resonant modes having their respective different associated resonance frequencies, wherein the resonance frequency values do increase with increasing number of the normal mode.

[0087] For example, in the exemplary illustrative case of the clamped-clamped bar according to Fig. 4, the ratio of resonant frequencies can be calculated to be approximately 1 (n=1) : 2.75 (n=2) : 5.40 (n=3) : 8.93 (n=4) : 13.34 (n=5): 18:64 (n=6): 24.81 (n=7) : 31.87 (n=8) : 39.81 (n=9) : 48.63 (n=10).

[0088] Specifically, for the clamped-clamped bar vibrations, the mode shapes for the normal modes n for a beam of length L with constant cross sectional area A and mass density ρ can be written as:

$$W_n(x) = \cos(k_n x) - \cosh(k_n x) - \gamma_n(\sin(k_n x) - \sinh(k_n x)) \;\; for\; x \in [0, L]$$

with

$$\gamma_n = \frac{\cos(k_n L) - \cosh(k_n L)}{\sin(k_n L) - \sinh(k_n L)}$$

and

$$k_1 L = 4{,}7300$$

$$k_2L = 7{,}8532$$

$$k_3L = 10{,}996$$

$$k_nL \approx (2n+1)\frac{\pi}{2}$$

for

$$n = 4{,}5{,}6, \ldots$$

with respective associated resonance frequencies

$$f_n = \frac{1}{2\pi}(k_n)^2\sqrt{\frac{EI_y}{\rho A}}$$

where E represents Young's modulus and I_y represents the area moment of inertia (also referred to as second moment of area). These mode shapes $W_n(x)$ are the ones exemplarily shown in Fig. 4 for n = 1 up to n = 10.

[0089] In another exemplary scenario of a vibrating bar with hinged ends of the bar on both sides, the ratio of resonant frequencies can be calculated to be increasing with the square of n, i.e. as 1 (n=1) : 4 (n=2) : 9 (n=3) : 16 (n=4), etc.

[0090] Specifically, for the bar vibrations of a vibrating bar with hinged ends of the bar on both sides, the mode shapes for the normal modes n for a beam of length L and mass M can be written as:

$$W_n(x) = \sin(k_n x) \quad for\ x \in [0, L]$$

with

$$k_nL = n\pi$$

for

$$n = 1{,}2{,}3 \ldots$$

with respective associated resonance frequencies

$$f_1 = \frac{1}{2\pi}\left(\frac{\pi}{L}\right)^2\sqrt{\frac{EI_y}{\rho A}}$$

and

$$f_n = n^2 f_1$$

for

$$n = 2{,}3{,}4, \ldots$$

where E represents Young's modulus and I_y represents the area moment of inertia (also referred to as second moment of area).

[0091] In any case, even for more complex structures and/or attachment scenarios, it remains true that the resonance frequencies (natural frequencies) associated with the respective normal modes increase with increasing normal mode number.

[0092] In more complex systems, such as MEMS designs exemplarily described below, it still remains true that the values of the resonance frequencies depend on the moments of inertia (e.g. depending on the material distribution, e.g. affected by the structure design) of the oscillating system and the stiffness of the springs in the oscillating system, so that the designs can be tuned, by tuning the spring stiffness of springs and/or the moments of inertia, allowing to tune the design as to achieve desired values of the resonance frequencies. It is further possible to selectively tune portions of the device layer structure design affecting certain normal modes over other normal modes, so as to tune ratios of resonance frequencies of different normal modes based on desired target frequency ratios.

[0093] In view of the above, an exemplary underlying principle of the present disclosure is that the device layer of a micromirror, such as, e.g., a MEMS-based micromirror (1D or 2D micromirror) oscillating with respect an axis (e.g. among one or more axes) can be operated to oscillate in different transverse normal modes (e.g. even-numbered normal modes for transverse tilting oscillations such as in projection or scanning applications, or odd-numbered normal modes for transverse shift oscillations, e.g. for interferometry applications).

[0094] So, it has been recognized that it can be enabled to provide a single micromirror device product that can be resonant-operated in at least one axis substantially at two or more different resonance frequencies associated with the respective different transverse normal modes associated with that respective axis, thereby enabling at least two efficient resonant operation modes of the same micromirror suitable for different applications and/or different functions.

[0095] Accordingly, the same micromirror device can be operated at two or more different resonance frequencies in at least one axis, and it is also exemplarily possible to switch between the different normal modes/resonant frequencies, for example, to provide different scan or projection patterns with the same device depending on user preferences and/or requirements of application.

[0096] Such principle of operation will be explained exemplarily in connection with an exemplary 2D micromirror design in the following.

[0097] It is to be noted that the principle can be applied to various different structural micromirror designs and the following structural aspects of the micromirror design are merely exemplarily described for illustrative purposes. Especially, the principle can be broadly applied also to 1D micromirror designs, e.g. for 1D bar code scanning applications.

[0098] **Fig. 5** is a schematic exemplary top view of a device layer 100 of an apparatus according to an exemplary embodiment according to an exemplary micromirror structure 10. The device layer 100 exemplarily includes a frame 110 which exemplarily functions as a rigid frame of the structure 10.

[0099] In the middle of the micromirror structure 10, the device layer 100 exemplarily includes a mirror support member 170 which exemplarily supports a mirror 300 (e.g. formed by a mirror layer formed on or above the mirror support member 170 of the device layer 100).

[0100] The structure 10 is exemplarily configured to enable actuated oscillations of the mirror 300 about two axes A1 and A2 driven by actuators 211 to 214 of an actuator layer 200. Such actuators 211 to 214 may, in some exemplary embodiments, be realized as piezoelectric actuators, e.g., formed from or by piezoelectric material, such as by a structured piezoelectric layer being provided on the device layer 100. However, additionally or alternatively, also other types of actuators can be used, e.g., electromagnetic actuated comb structures, capacitor-based actuators and/or other types of actuators known in MEMS technology.

[0101] Exemplarily, the actuators 211 to 214 are arranged on respective paddle portions 121 to 124 of a paddle structure 120 of the device layer 100 that are connected to the frame 110 on opposite sides, providing the anchor portions for the inner movable portions of the device layer 100 held by the outer rigid frame 110 at the anchor portions.

[0102] The paddle portions 121 to 124 of a paddle structure 120 of the device layer 100 can exemplarily act as oscillating levers that are rigidly connected to the frame 110 on one side thereof and can perform already some oscillating deformations on the side facing the inner portions of the device layer 100.

[0103] The inner mirror support member 170 of the device layer 100 is exemplarily connected by spring portions 161 and 162 of an inner spring structure 160 of the device layer 100 to an exemplarily closed inner frame portion 140 of the device layer 100 that exemplarily surrounds the inner mirror support member 170 of the device layer 100.

[0104] Exemplarily the spring portions 161 and 162 of the inner spring structure 160 of the device layer 100 are arranged on opposite sides of the inner mirror support member 170 of the device layer 100, and the spring portions 161 and 162 exemplarily extend along the axis A2.

[0105] Exemplarily, the spring portions 161 and 162 of the inner spring structure 160 of the device layer 100 are provided as longitudinal torsion springs in Fig 5, but other spring shapes and types, such as, e.g., doubled torsion springs or meander-shaped springs can be used alternatively or additionally.

[0106] The inner frame portion 140 of the device layer 100 is exemplarily connected by spring portions 131 and 132 of an outer spring structure 130 of the device layer 100 to the respective paddle portions 121 to 124 of the paddle structure 120 of the device layer 100.

[0107] Exemplarily, the spring portions 131 and 132 of the outer spring structure 130 of the device layer 100 are arranged on opposite sides of the inner frame portion 140 of the device layer 100, and the spring portions 131 and 132 of the outer spring structure 130 of the device layer 100 exemplarily extend along the axis A1.

[0108] Exemplarily, the spring portions 131 and 132 of the outer spring structure 130 are provided as T-shaped torsion springs in Fig 5, but other spring shapes and types, such as, e.g., doubled torsion springs or meander-shaped springs can be used alternatively or additionally.

[0109] The driven oscillation of the mirror 300 about the axis A1 can be actuated, exemplarily, in that the actuators 211 and 212 on the right side of axis A1 in Fig. 5 are driven in counter-phase to the actuators 213 and 214 on the left side of axis A1 in Fig. 5. Preferably, for reasons of energy efficiency, the oscillation about the axis A1 is driven substantially at a respective resonance frequency of the structure 10 associated with oscillations about the axis A1.

[0110] On the other hand, the driven oscillation of the mirror 300 about the axis A2 can be actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in counter-phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5. Preferably, for reasons of energy efficiency, the oscillation about the axis A2 is driven substantially at a respective resonance frequency of the structure 10 associated oscillations about the axis A2.

[0111] As discussed above, it is possible to drive oscillations with respect to each of the axes A1 and A2 independently. Furthermore, by separately (individually) actuating the four actuators 211 to 214 with respective drive signals and by appropriately modulating the respective drive signals, both axes A1 and A2 can be operated simultaneously, e.g., such that the mirror 300 is driven to oscillate about the axis A1 substantially at a resonance frequency of the axis A1 and about the axis A2 substantially at a resonance frequency of the axis A2, so that a Lissajous pattern can be projected or scanned with a light beam reflected from the oscillating mirror 300, e.g., such that a Lissajous pattern according to Figs. 2A, 2B, 3A, or 3B can be produced.

[0112] Accordingly, each actuator 211 to 214 can be driven by their respective separate drive signal provided via the respective signal lines 401 to 403 of the contacting 400 exemplarily shown in Fig. 5. Such drive signals can be generated by a controller of the micromirror device (see exemplary embodiments below).

[0113] **Fig. 6** is a schematic exemplary cross-sectional view of the device layer 100 of Fig. 5 along the axis A1. Exemplarily, the device layer 100 is provided as a MEMS layer structure made from plural layers as known from MEMS technology. Exemplarily, plural layers of the MEMS layer structure are exemplarily shown. The layer structure of the device layer 100 is not limited and can be provided in various layer configurations, e.g., as known in the art.

[0114] **Fig. 7** is a schematic exemplary cross-section view of an apparatus according to an exemplary embodiment. The apparatus 20 exemplarily includes the device layer 100 of Fig. 6 and is exemplarily closed from the bottom side with a base member 8 and is exemplarily closed from the top side with a preferably transparent top member 7. In some exemplary embodiments, the apparatus 20 may have a low-pressure atmosphere, preferably a vacuum, inside between the base member 8 and the top member 7 so as to allow for even more efficient oscillation of the mirror 300 of the apparatus 20.

[0115] As explained above, the tilt oscillations of the mirror 300 about the axis A2 (e.g. for scanning and/or projection applications) can be resonant-operated in different even-numbered transverse normal modes of the device layer 100 (associated with axis A1, e.g., as shown in Figs. 8A to 8D). This will be exemplarily illustrated with respect to the second to eighth even-numbered transverse normal modes n = 2, n = 4, n = 6, and n = 8 in the following.

[0116] **Fig. 8A** is a schematic exemplary cross-sectional view of the exemplary device layer 100 of Fig. 5 along the axis A1 in a state of exemplary oscillations of the mirror 300 about the axis A2 (e.g. for scanning and/or projection applications) in the second transverse normal mode (n = 2) of oscillation (i.e. substantially at the resonance frequency associated with the second transverse normal mode).

[0117] Accordingly, if the driven oscillation of the mirror 300 about the axis A2 is actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in counter-phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5 substantially at the resonance frequency of the second transverse normal mode of the device layer 100 associated with axis A2, then the device layer 100 will oscillate according to the second transverse normal mode as exemplarily illustrated in Fig. 8A, and the mirror 300 is driven to perform an oscillating tilt movement about the axis A2 substantially at the resonance frequency of the second transverse normal mode.

[0118] As can be seen in Fig. 8A, the second transverse normal mode operates such that the actuated outer portions (e.g. on paddle portions 123 and 124 in the dashed background of Fig. 8A) move in phase with the inner oscillations of the mirror 300.

[0119] **Fig. 8B** is a schematic exemplary cross-sectional view of the exemplary device layer 100 of Fig. 5 along the axis A1 in a state of exemplary oscillations of the mirror 300 about the axis A2 (e.g. for scanning and/or projection applications) in the fourth transverse normal mode (n = 4) of oscillation (i.e. substantially at the resonance frequency associated with the fourth transverse normal mode).

[0120] Accordingly, if the driven oscillation of the mirror 300 about the axis A2 is actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in counter-phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5 substantially at the resonance frequency of the fourth transverse normal mode of the device layer 100, then the device layer 100 will oscillate according to the fourth transverse normal mode as exemplarily illustrated in Fig. 8B, and the mirror 300 is driven to perform an oscillating tilt movement about the axis A2 substantially at the resonance frequency of the fourth transverse normal mode (being larger than the resonance frequency of the second transverse normal mode).

[0121] As can be seen in Fig. 8B, the fourth transverse normal mode operates such that the actuated outer portions (e.g. on paddle portions 123 and 124 in the dashed background of Fig. 8B) move in counter-phase with the inner oscillations of the mirror 300.

[0122] **Fig. 8C** is a schematic exemplary cross-sectional view of the exemplary device layer 100 of Fig. 5 along the axis A1 in a state of exemplary oscillations of the mirror 300 about the axis A2 (e.g. for scanning and/or projection applications) in the sixth transverse normal mode (n = 6) of oscillation (i.e. substantially at the resonance frequency associated with the sixth transverse normal mode).

[0123] Accordingly, if the driven oscillation of the mirror 300 about the axis A2 is actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in counter-phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5 substantially at the resonance frequency of the sixth transverse normal mode of the device layer 100, then the device layer 100 will oscillate according to the sixth transverse normal mode as exemplarily illustrated in Fig. 8C, and the mirror 300 is driven to perform an oscillating tilt movement about the axis A2 substantially at the resonance frequency of the sixth transverse normal mode (being larger than the resonance frequency of the fourth transverse normal mode).

[0124] As can be seen in Fig. 8C, the sixth transverse normal mode operates such that the actuated outer portions (e.g. on paddle portions 123 and 124 in the dashed background of Fig. 8B) move in phase with the inner oscillations of the mirror 300.

[0125] **Fig. 8D** is a schematic exemplary cross-sectional view of the exemplary device layer 100 of Fig. 5 along the axis A1 in a state of exemplary oscillations of the mirror 300 about the axis A2 (e.g. for scanning and/or projection applications) in the eighth transverse normal mode (n = 8) of oscillation (i.e. substantially at the resonance frequency associated with the eighth transverse normal mode).

[0126] Accordingly, if the driven oscillation of the mirror 300 about the axis A2 is actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in counter-phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5 substantially at the resonance frequency of the eighth transverse normal mode of the device layer 100, then the device layer 100 will oscillate according to the eighth transverse normal mode as exemplarily illustrated in Fig. 8D, and the mirror 300 is driven to perform an oscillating tilt movement about the axis A2 substantially at the resonance frequency of the eighth transverse normal mode (being larger than the resonance frequency of the sixth transverse normal mode).

[0127] As can be seen in Fig. 8D, the eighth transverse normal mode operates such that the actuated outer portions (e.g. on paddle portions 123 and 124 in the dashed background of Fig. 8B) move in counter-phase with the inner oscillations of the mirror 300.

[0128] In connection with Figs. 8A to 8D above, exemplary utilization of even-numbered transverse normal modes have been discussed, which can be used to actuate tilt oscillations of the mirror 300, e.g. for scanning and/or projection applications. However, also the even-numbered transverse normal modes can be utilized for applications in which a transverse shift of the mirror 300 may be utilized, e.g. in interferometry applications. This will be exemplarily illustrated with reference to Figs. 9A to 9C below.

[0129] More specifically, the transverse shift oscillations of the mirror 300 in a direction orthogonal to the plane of axes A1 and A2 (e.g. for interferometry applications) can be resonant-operated in different odd-numbered transverse normal modes of the device layer 100. This will be exemplarily illustrated with respect to the first to fifth odd-numbered transverse normal modes n = 1, n = 3, and n = 5 in the following.

[0130] **Fig.9A** is a schematic exemplary cross-sectional view of the exemplary device layer 100 of **Fig. 5** along the axis A1 (e.g. for interferometry applications) in a state of exemplary oscillations in the first transverse normal mode (n = 1) of oscillation (i.e. substantially at the resonance frequency associated with the first transverse normal mode).

[0131] Accordingly, if the driven shift oscillation of the mirror 300 is actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5 substantially at the resonance frequency of the first transverse normal mode of the device layer 100, then the device layer 100 will oscillate according to the first transverse normal mode as exemplarily illustrated in Fig. 9A, and the mirror 300 is driven to perform an oscillating shift movement (along a direction orthogonal to the plane of the axes A1 and A2) substantially at the resonance frequency of the first transverse normal mode (being smaller than the resonance frequency of the second transverse normal mode).

[0132] As can be seen in Fig. 9A, the first transverse normal mode operates such that the actuated outer portions (e.g. on paddle portions 123 and 124 in the dashed background of Fig. 9A) move in phase with the inner shift oscillations of the mirror 300.

[0133] **Fig. 9B** is a schematic exemplary cross-sectional view of the exemplary device layer 100 of **Fig. 5** along the axis A1 (e.g. for interferometry applications) in a state of exemplary oscillations in the third transverse normal mode (n = 3) of oscillation.

[0134] Accordingly, if the driven shift oscillation of the mirror 300 is actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5 substantially at the resonance frequency of the third transverse normal mode of the device layer 100, then the device layer 100 will oscillate according to the third transverse normal mode as exemplarily illustrated in Fig. 9B, and the mirror 300 is driven to perform an oscillating shift movement (along a direction orthogonal to the plane of the axes A1 and A2) substantially at the resonance frequency of the third transverse normal mode (being larger than the resonance frequency of the first and second transverse normal modes, and being smaller than the resonance frequency of the fourth transverse normal mode).

[0135] As can be seen in Fig. 9B, the third transverse normal mode operates such that the actuated outer portions (e.g. on paddle portions 123 and 124 in the dashed background of Fig. 9B) move in counter-phase with the inner shift oscillations of the mirror 300.

[0136] **Fig. 9C** is a schematic exemplary cross-sectional view of the exemplary device layer 100 of **Fig. 5** along the axis A1 (e.g. for interferometry applications) in a state of exemplary oscillations in the fifth transverse normal mode (n = 5) of oscillation.

[0137] Accordingly, if the driven shift oscillation of the mirror 300 is actuated in that the actuators 211 and 213 on the lower side of axis A2 in Fig. 5 are driven in phase to the actuators 212 and 214 on the upper side of axis A2 in Fig. 5 substantially at the resonance frequency of the fifth transverse normal mode of the device layer 100, then the device layer 100 will oscillate according to the fifth transverse normal mode as exemplarily illustrated in Fig. 9C, and the mirror 300 is driven to perform an oscillating shift movement (along a direction orthogonal to the plane of the axes A1 and A2) substantially at the resonance frequency of the fifth transverse normal mode (being larger than the resonance frequency of the third and fourth transverse normal mode, and being smaller than the resonance frequency of the sixth transverse normal mode).

[0138] As can be seen in Fig. 9C, the fifth transverse normal mode operates such that the actuated outer portions (e.g. on paddle portions 123 and 124 in the dashed background of Fig. 9A) move in phase with the inner shift oscillations of the mirror 300.

[0139] **Fig.10** is a schematic exemplary view of a curve of amplitude as a function of frequency at an exemplary resonance frequency f_n of an n-th normal mode of oscillation (with n = 1, 2, 3, ..., or higher positive integer).

[0140] As discussed above and below, operating the micromirror in some exemplary aspects includes driving at least one n-th transverse normal mode substantially at the resonance frequency f_n associated with the n-th transverse normal mode. This can provide the benefit that sufficiently large oscillation amplitudes can be achieved very efficiently due to the resonant operation.

[0141] The curve of Fig. 10 is an illustrative example showing that the driving signal at the resonance frequency f_n achieves the highest amplitude $A_{MAX,n}$ (at least locally in the frequency spectrum, since amplitude maximum values may be different at different resonant frequencies). For frequencies (locally) lower or smaller than the resonance frequency f_n, the achieved driven amplitude decreases, as exemplarily illustrated in Fig. 10.

[0142] Fig. 10 can be used to illustrate the quality factor QF_n which is defined as the ratio of the resonance frequency value and the full width of the frequency curve around the resonance frequency f_n at the height of the curve, where the amplitude has decreased by half with respect to the (local) amplitude maximum value $A_{MAX,n}$, i.e. at $A_{MAX,n}/2$, referred to as FWHM (full width at half maximum):

$$QF_n = \frac{f_n}{FWHM_n}$$

[0143] When driving the micromirror substantially at a resonance frequency f_n, so as to efficiently achieve sufficient amplitude values, it may be preferred that the driving frequency is sufficiently close to the respective resonance frequency f_n, which may be defined relative to the respective resonance frequency f_n (e.g. with a driving frequency f_d within an interval $f_n \cdot (1 \pm q)$ with q preferably being 0,1 or lower).

[0144] More preferably the driving frequency f_D may be chosen depending on the respective quality factor QF_n associated with the respective resonance frequency f_n.

[0145] Preferably, in some exemplary aspects, driving the micromirror (or one axis thereof) substantially at the respective resonance frequency may mean, according to the present disclosure, that the driving frequency f_D is selected based on the quality factor QF_n associated with the respective resonance frequency f_n of the selected normal mode to be driven, e.g. as follows:

$$\frac{f_D}{f_n} \epsilon \left[1 - \frac{1}{p \cdot QF_n}, 1 + \frac{1}{p \cdot QF_n}\right]$$

[0146] Preferably, when driving the micromirror device substantially at the resonance frequency, this may mean preferably that p is equal to 1 or more, such as $p \geq 1$, or more preferably with $p \geq 2$, or even more preferably with $p \geq 3$ (see e.g. the example of Fig. 10).

[0147] In such exemplary case, the driving frequency can be preferably selected within the interval as follows:

$$\frac{f_D}{f_n} \in \left[1 - \frac{1}{3 \cdot QF_n}, 1 + \frac{1}{3 \cdot QF_n}\right]$$

[0148] This corresponds to a driving frequency f_D utilized within the following interval, as exemplarily illustrated in Fig. 10, with respect of the resonance frequency f_n associated with the selected n-th transverse normal mode to be substantially driven:

$$f_D \in \left[f_n - \frac{FWHM_n}{3}, f_n + \frac{FWHM_n}{3}\right]$$

[0149] **Fig. 11** is a schematic functional block diagram of an apparatus 20 according to some exemplary embodiments. Exemplarily, the apparatus 20 includes the micromirror 10 and a controller 30 configured to drive the micromirror device 10.

[0150] The controller 30 may exemplarily include a processor and/or microchip and/or a memory including software and/or software for executing the control functions. Accordingly, the controller 30 may include hardware and/or software implementations of control functions to be executed by the controller 30 so as to control operation of the apparatus 20, including controlling operation of the micromirror.

[0151] The micromirror device 10 exemplarily includes the actuators 211 to 214 and can be provided according to the exemplary configuration of Figs. 5 to 7 or other exemplary implementations in which a mirror 300 can be driven to oscillate about two axes (exemplary 2D micromirror), e.g., such as exemplarily shown in Fig. 14 described below.

[0152] Furthermore, the apparatus 20 may exemplarily include a light source 40 (such as a laser, for example) configured to direct a light beam (e.g. a laser beam, or multiple laser beams) onto the mirror 300 of the micromirror device, for applications such as scanning applications (1D and/or 2D), projection applications (2D) and/or interferometry applications (1D and/or 2D).

[0153] The controller 30 exemplarily includes axis drive signal generators 701 and 702. Exemplarily, the axis drive signal generator 701 is configured to generate a drive signal for oscillation of one of the axes of the micromirror device 10, and the exemplary drive signal generator 702 is exemplarily configured to generate a drive signal for oscillation of the other one of the axes of the micromirror device 10.

[0154] Exemplarily, the controller 30 further includes a switch 800 configured to switch between two or more operation modes of the apparatus 20. Exemplarily, the two or more operation modes of the apparatus 20 are associated with different operation modes in which different normal modes of vibration are actuated for at least one of the axes of the micromirror device 10, for example, to produce different Lissajous patterns in scanning or projection applications of the apparatus 20, e.g. in 2D scanning and/or 2D projection applications.

[0155] In case of 1D applications, this may be utilized to switch the one axis operation between different resonant-operated frequencies for the 1D scanning application (and/or 1D interferometry application).

[0156] In accordance with the above, at least one of the (one or more) axes of the micromirror device 10 can be operated to oscillate in at least two even-numbered transverse normal modes at different associated resonance frequencies of the respective transverse normal modes (e.g. Figs. 8A to 9C above, etc.).

[0157] For example, the axis drive signal generator 701 is configured to generate a drive signal for oscillation of one of the axes of the micromirror device 10 substantially oscillating at the resonance frequency of an even-numbered transverse normal mode of the respective axis or at the resonance frequency of another even-numbered transverse normal mode of the respective axis depending on the operating mode set by the switch 800.

[0158] In some exemplary embodiments, the switch 800 can be implemented by a mechanical and/or electrical switch or other type of switch. In some further exemplary embodiments, the switch 800 can be implemented by hardware and/or software, e.g., using a register or memory that stores computer-readable information according to the selected operation mode.

[0159] In some exemplary embodiments, the switch 800 is configured to switch between two or more operation modes of a first axis of the micromirror 10 of the apparatus 20 and/or between two or more operation modes of a second axis of the micromirror 10 of the apparatus 20.

[0160] Exemplarily, the two or more operation modes of the first axis are associated with different operation modes in which different transverse normal modes of vibration are actuated for the first axis of the micromirror device 10, and/or the two or more operation modes of the second axis are associated with different operation modes in which different transverse normal modes of vibration are actuated for the second axis of the micromirror device 10.

[0161] For example, the axis drive signal generator 701 is configured to generate a drive signal for oscillation of a first axis of the micromirror device 10 substantially oscillating at the resonance frequency of an even-numbered normal mode of the respective first axis or at the resonance frequency of another even-numbered normal mode of the respective first axis depending on the operating mode set by the switch 800.

[0162] For example, the axis drive signal generator 702 is configured to generate a drive signal for oscillation of a second axis of the micromirror device 10 substantially oscillating at the resonance frequency of an even-numbered normal mode of the respective second axis or at the resonance frequency of another even-numbered normal mode of the respective second axis depending on the operating mode set by the switch 800.

[0163] Further exemplary, the controller 30 comprises an actuator signal generator 600 configured to generate the actuator drive signals for the actuators 211 to 214 of the micromirror device 10 based on the axis drive signals from the axis drive signal generators 701.

[0164] For example, according to the exemplary configuration of Fig. 5, oscillation about the first axis A1 is driven by driving the actuators 211 and 212 in counter-phase to the actuators 213 and 214, and oscillation about the second axis A2 is driven by driving the actuators 211 and 213 in counter-phase to the actuators 212 and 214.

[0165] Accordingly, for the generation of the drive signal for actuator 211, the actuator signal generator 600 can generate a signal combining the drive signals from the axis drive signal generators 701 and 702, while, for the generation of the drive signal for actuator 214, the actuator signal generator 600 can generate a signal combining signals being respectively in counter-phase to the respective drive signals from the axis drive signal generators 701 and 702.

[0166] For the generation of the drive signal for actuator 212, the actuator signal generator 600 can generate a signal combining the drive signal from the axis drive signal generator 701 with a signal being in counter-phase to the drive signal from the axis drive signal generator 702, and, for the generation of the drive signal for actuator 213, the actuator signal generator 600 can generate a signal combining a signal being in counter-phase to the drive signal from the axis drive signal generator 701 with the drive signal from the axis drive signal generator 702.

[0167] The drive signals generated by the actuator signal generator 600 can be output to the actuators 211 to 214 via the signal outputs 501 to 504 of the controller 20 being respectively connected to the connection lines 401 to 404 respectively connected to the actuators 211 to 214.

[0168] In some exemplary embodiments, the controller 30 can be configured to drive operation in accordance with one or more of the following exemplary methods of operation.

[0169] **Fig. 12** is a schematic flow chart exemplarily illustrating a method of operating a 2D micromirror 10 according to some exemplary embodiments, for example, for a 2D scanning or projection application.

[0170] Exemplarily, the method includes a step S101 of driving the first axis of two axes of the 2D micromirror 10 in resonance substantially at a resonance frequency of the first axis of the 2D micromirror 10, and a step S102 of driving the second axis of the two axes of the 2D micromirror 10 in resonance substantially at a resonance frequency of the second axis of the 2D micromirror 10. This is exemplarily referred to as first operation mode.

[0171] Exemplarily, the resonance frequency of the second axis of the 2D micromirror 10 in the first operation mode is a resonance frequency of an n-th transverse normal mode of the second axis (e.g. with even numbered n, such as n = 2, 4, 6, 8, or higher; see e.g. the examples of Figs. 8A to 8D), and the second axis can be driven substantially at the resonance frequency of the n-th transverse normal mode of the second axis in step S102.

[0172] Accordingly, by reflecting a light beam on the oscillating mirror of the micromirror 10 driven according to S101 and S102, the 2D-driven oscillations in the first and second axes of the micromirror 10 are suitable to produce a Lissajous pattern of a first type; see e.g. step S103 of projecting or scanning according to a first Lissajous pattern, when the micromirror is driven in the first operation mode.

[0173] Exemplarily, the method further includes a step S104 of switching from the first operation mode into a second operation mode.

[0174] Exemplarily, when it is switched into the second operation mode in step S104, the method includes a step S105 of driving the first axis of two axes of the 2D micromirror 10 in resonance substantially at a resonance frequency of the first axis of the 2D micromirror 10. In some exemplary embodiments, the first axis can be operated substantially at the same resonance frequency in both operation modes, e.g., in both steps S101 and S105.

[0175] Exemplarily, when it is switched into the second operation mode in step S104, the method includes a step S106 of driving the second axis of the two axes of the 2D micromirror 10 in resonance substantially at another resonance frequency of the second axis of the 2D micromirror 10. This is exemplarily referred to as second operation mode operation mode.

[0176] Exemplarily, the resonance frequency of the second axis of the 2D micromirror 10 in the second operation mode is a resonance frequency of an m-th transverse normal mode of the second axis (e.g. with even numbered m, such as m = 2, 4, 6, 8, or higher; see e.g. the examples of Figs. 8A to 8D; but with m being different than n of the first operation mode), and the second axis can be driven substantially at the resonance frequency of the m-th transverse normal mode of the second axis in step S106.

[0177] Accordingly, by reflecting a light beam on the oscillating mirror of the micromirror 10 driven according to S105 and S106, the 2D-driven oscillations in the first and second axes of the micromirror 10 are suitable to produce a Lissajous pattern of a second type different from the Lissajous pattern of the first type; see e.g. step S107 of projecting or scanning according to a second Lissajous pattern, when the micromirror is driven in the second operation mode.

[0178] In some exemplary embodiments, the micromirror can be tuned such that the resonance frequency of the first axis (steps S101 and S105) is similar (preferably with a difference substantially equal or lower than 20% or even more preferably substantially equal or lower than 10%) or substantially equal to the resonance frequency of the second axis in the first operation mode (step S02), so that step S103 produces a homogenous Lissajous pattern (such as Figs. 2A and Fig. 2B).

[0179] Then, in exemplary embodiments, in which m is smaller than n (e.g. n = 4 and m = 2, or n = 6 and m = 2, or n = 6 and m = 4), the second axis is driven in the second operation mode (substantially in resonance) at a frequency that is smaller (i.e. slower) compared to the operation in the first operation mode.

[0180] Alternatively, in exemplary embodiments, in which m is larger than n (e.g. n = 2 and m = 4, or n = 2 and m = 6, or n = 4 and m = 2), the second axis is driven in the second operation mode (substantially in resonance) at a frequency that is larger (i.e. faster) compared to the operation in the first operation mode.

[0181] In both cases, the second operation mode involves driven oscillations in which the driven frequencies of the first and second axes are comparatively different, and step S107 produces a more raster-like Lissajous pattern (such as Figs. 3A and Fig. 3B).

[0182] In some further exemplary embodiments, the micromirror can be tuned such that the resonance frequency of the first axis (steps S101 and S105) is similar (preferably with a difference substantially equal or lower than 20% or even more preferably substantially equal or lower than 10%) or substantially equal to the resonance frequency of the second axis in the second operation mode (step S06), so that step S107 produces a homogenous Lissajous pattern (such as Figs. 2A and Fig. 2B).

[0183] Then, in exemplary embodiments, in which m is smaller than n (e.g. n = 4 and m = 2, or n = 6 and m = 2, or n = 6 and m = 4), the second axis is driven in the first operation mode (substantially in resonance) at a frequency that is larger (i.e. faster) compared to the operation in the second operation mode.

[0184] Alternatively, in exemplary embodiments, in which m is larger than n (e.g. n = 2 and m = 4, or n = 2 and m = 6, or n = 4 and m = 2), the second axis is driven in the first operation mode (substantially in resonance) at a frequency that is smaller (i.e. slower) compared to the operation in the first operation mode.

[0185] In both cases, the first operation mode involves driven oscillations in which the driven frequencies of the first and second axes are comparatively different, and step S103 produces a more raster-like Lissajous pattern (such as Figs. 3A and Fig. 3B).

[0186] In some further exemplary embodiments, it is possible to switch from the first operation mode to the second operation mode and/or to switch back to the first operation mode, or vice versa.

[0187] For example, in projection applications in which the micromirror is used to project images, such switching between operation modes to switch the projection patterns between different types of Lissajous patterns, while maintaining to drive both axes substantially in efficient resonant operation, can be performed for different purposes.

[0188] For example, in some exemplary embodiments, it is possible to provide a user-selectable option such that the user can switch between the first and second operation modes so as to select the image projection pattern that provides the subjectively better viewing experience to them. For example, the user can be provided with a physical switch or button and/or a user-selectable interface option, such as by a menu screen or the like, enabling that the user switches between the first and second operation modes and/or user-selects the operation mode to be used (e.g. by setting a user-preference selected operation mode).

[0189] Alternatively or additionally, in some exemplary embodiments, it is possible to switch operation modes according to the aspect ratio of the projected image, e.g. when the first Lissajous pattern of step S103 is optimized for a first aspect ratio of the projected image, and the second Lissajous pattern of step S107 is optimized for a different second aspect ratio of the projected image.

[0190] Alternatively or additionally, in some exemplary embodiments, it is possible to switch operation modes according to the projection type, e.g. when the first Lissajous pattern of step S103 is optimized for projecting stationary images, such as menu screens, photos, etc., and the second Lissajous pattern of step S107 is optimized for a different projection type, e.g. when the second Lissajous pattern of step S107 is optimized for projecting movies or other type of videos.

[0191] Alternatively or additionally, in some exemplary embodiments, it is possible to switch operation modes according to the desired frame rate, e.g. when the first Lissajous pattern of step S103 is optimized for projecting a first frame rate, and the second Lissajous pattern of step S107 is optimized for a different second frame rate (larger or smaller than the first frame rate).

[0192] Alternatively or additionally, in some exemplary embodiments, it is possible to switch operation modes according to the desired image resolution of the projected images, e.g. when the first Lissajous pattern of step S103 is optimized for projecting an image resolution, and the second Lissajous pattern of step S107 is optimized for a different second image resolution (larger or smaller than the first image resolution).

[0193] When combining the above examples, it can be beneficial, according to some exemplary embodiments, to provide switching between three or more operation modes, wherein the second axis is driven in different transverse normal modes in each of the different operation modes.

[0194] Furthermore, it is also possible to operate not only the second axis in different transverse normal modes of the second axis, but to additionally enable switching the first axis among different transverse normal modes of the first axis, as is exemplarily shown in connection with Fig. 13, so as to provide further options of two or more operation modes with the same micromirror device (in which both axes are efficiently resonant-operated).

[0195] **Fig. 13** is a schematic flow chart exemplarily illustrating another method of operating a 2D micromirror 10 according to some further exemplary embodiments, for example, for 1D or 2D scanning applications, 2D projection applications, and/or 1D or 2D interferometry applications.

[0196] Herein, while the exemplary Fig. 12 only related to 2D scanning or projection applications, Fig. 13 describes the more broader concept with regard to 1D or 2D scanning applications, 2D projection applications, and/or 1D or 2D interferometry applications. In case of 1D applications, no further axis may present, and for 2D applications, another second axis may be driven as explained in other exemplary embodiments.

[0197] Exemplarily, the method includes a step S102a of driving an axis of one or more axes of the micromirror in resonance substantially at a resonance frequency of the axis of the micromirror. This is exemplarily referred to as first operation mode.

[0198] Exemplarily, in step S102a, the driven frequency of the axis of the micromirror in the first operation mode substantially is a resonance frequency of an n-th transverse normal mode of the axis (e.g. with even numbered n, such as n = 2, 4, 6, 8, or higher; see e.g. the examples of Figs. 8A to 8D; or with odd numbered n, such as n = 1, 3, 5, 7, or higher; see e.g. the examples of Figs. 9A to 9C).

[0199] Accordingly, by step S103a of reflecting a light beam on the oscillating mirror of the micromirror 10 driven according to S102a, the selected application can be operated, when the micromirror is driven in the first operation mode. That is, in the exemplary case of 1D, even numbered n, such as n = 2, 4, 6, 8, or higher, allows for 1D scanning applications and odd-numbered n, such as n = 1, 3, 5, 7, or higher, allows for interferometry applications.

[0200] Exemplarily, the method further includes a step S104a of switching from the first operation mode into a second operation mode.

[0201] Exemplarily, when it is switched into the second operation mode in step S104a, the method includes a step S106a of driving the axis of the micromirror in resonance substantially at another resonance frequency of the axis of the micromirror. This is exemplarily referred to as second operation mode.

[0202] Exemplarily, in step S106a, the driven frequency of the axis of the micromirror in the second operation mode substantially is a resonance frequency of an m-th transverse normal mode of the axis (e.g. with even numbered m, such as m = 2, 4, 6, 8, or higher; see e.g. the examples of Figs. 8A to 8D; or with odd numbered m, such as m = 1, 3, 5, 7, or higher; see e.g. the examples of Figs. 9A to 9C; but with m being different than n of the first operation mode).

[0203] Accordingly, by step S107a of reflecting a light beam on the oscillating mirror of the micromirror 10 driven according to S106a, the selected application can be operated, when the micromirror is driven in the second operation mode. That is, in the exemplary case of 1D, even numbered m, such as m = 2, 4, 6, 8, or higher, allows for 1D scanning applications and odd-numbered m, such as m = 1, 3, 5, 7, or higher, allows for interferometry applications.

[0204] This allows to switch between the same application (e.g. scanning, projection or interferometry) being switched between different efficient resonant operation modes substantially driven at different resonance frequencies. Furthermore, when switching from odd-numbered modes to even-numbered modes or vice versa; this allows also to switch between different applications, including switching between projection/scanning and interferometry applications, or vice versa.

[0205] **Fig. 14** is a schematic exemplary top view of another device layer 100 of an apparatus according to some exemplary embodiments.

[0206] The exemplary device layer 100 of Fig. 14 is similar to the device layer 100 of Fig. 5 above. However, while the paddle portions 121 to 124 in Fig. 5 are exemplarily anchored to the frame 110 on opposite sides with respect to axis A2, the paddle portions 121 to 124 in Fig. 14 are exemplarily anchored to the frame 110 on opposite sides with respect to axis A1 and have portions extending in the direction of the axis A2 towards the attachment positions of the springs 131 and 132.

[0207] Accordingly, when actuating the actuators 211 and 213 in phase or counter-phase to the actuators 212 and 214, the transverse normal modes associated with axis A1 (e.g. similar to Figs. 8A to 9C) can be actuated. Then, the structure of the springs 131 and 132 and the inner frame portion 140 oscillate with modal shapes of the transverse normal modes associated with axis A1 (e.g. similar to Figs. 8A to 9C).

[0208] On the other hand, exemplarily, when actuating the actuators 211 and 212 in phase or counter-phase to the actuators 213 and 214, the transverse normal modes associated with axis A2 can be actuated. Then, the structure of the paddle portions 121 to 124, in particular the portions thereof extending in the direction of the axis A2, can oscillate with modal shapes of the transverse normal modes associated with axis A2 (e.g. similar the modal shapes of Fig. 4).

[0209] Further exemplarily, when the axes A1 and A2 are both driven in respective even-numbered transverse normal modes, this allows for 2D scanning or projection applications. On the other hand, further exemplarily, when the axes A1 and A2 are both driven in respective odd-numbered transverse normal modes, this allows for interferometry applications by the mirror 300 performing a shift oscillation in the direction orthogonal to the plane of axes A1 and A2. Accordingly, this allows for switching between different scanning(projection patterns, but also switching between different interferometry application modes with different efficient resonant-operated frequencies. Further exemplarily, this allows to switch between 2D scanning/projection applications and interferometry applications on the same micromirror device.

[0210] **Fig. 15** is a schematic flow chart exemplarily illustrating another method of operating a 2D micromirror 10 according to some further exemplary embodiments.

[0211] Exemplarily, the method includes a step S111 of driving the first axis of two axes of the 2D micromirror 10 in resonance substantially at a resonance frequency of the first axis of the 2D micromirror 10, and a step S112 of driving the second axis of the two axes of the 2D micromirror 10 in resonance substantially at a resonance frequency of the second axis of the 2D micromirror 10. This is exemplarily referred to as first operation mode.

[0212] Exemplarily, the resonance frequency of the first axis of the 2D micromirror 10 in the first operation mode in step S111 is substantially the resonance frequency of a k-th normal mode of the first axis (e.g. with even numbered k, such as k = 2, 4, 6, 8, or higher; or with odd numbered k, such as k = 1, 3, 5, 7, or higher), and the second axis can be driven substantially at the resonance frequency of the n-th normal mode of the second axis in step S112 (e.g. with even numbered n, such as n = 2, 4, 6, 8, or higher; or with odd numbered n, such as n = 1, 3, 5, 7, or higher).

[0213] Accordingly, by reflecting a light beam on the oscillating mirror of the micromirror 10 driven according to S111 and S112, the 2D-driven oscillations in the first and second axes of the micromirror 10 are suitable to produce a Lissajous pattern of a first type, if n and k are even-numbered; see e.g. step S113 of projecting or scanning according to a first Lissajous pattern, when the micromirror is driven in the first operation mode. Alternatively, if n and k are odd-numbered, an interferometry application can be performed.

[0214] Exemplarily, the method further includes a step S114 of switching from the first operation mode into a second operation mode.

[0215] Exemplarily, in the steps S115 and S116 of driving the first and second axes in the second operation mode, the resonance frequency of the first axis of the 2D micromirror 10 in the second operation mode in step S115 is substantially the resonance frequency of an i-th normal mode of the first axis (e.g. with even numbered i, such as i = 2, 4, 6, 8, or higher; or with odd numbered i, such as i = 1, 3, 5, 7, or higher; with i being different than k), and the second axis can be driven substantially at the resonance frequency of the m-th normal mode of the second axis in step S116 (e.g. with even numbered m, such as m = 2, 4, 6, 8, or higher; or with odd numbered m, such as m = 1, 3, 5, 7, or higher; with m being different from n). This is exemplarily referred to as second operation mode operation mode.

[0216] Accordingly, by reflecting a light beam on the oscillating mirror of the micromirror 10 driven according to S115 and S116, the 2D-driven oscillations in the first and second axes of the micromirror 10 are suitable to produce a Lissajous pattern of a second type different from the Lissajous pattern of the first type, if m and i are even-numbered; see e.g. step S117 of projecting or scanning according to a second Lissajous pattern, when the micromirror is driven in the second operation mode. Alternatively, if m and i are odd-numbered, an interferometry application can be performed.

[0217] Exemplarily, in some exemplary embodiments, the micromirror can be tuned such that the resonance frequencies of the first and second axes are similar (preferably with a difference substantially equal or lower than 20% or even more preferably substantially equal or lower than 10%) or substantially equal in the first operation mode, so that step S113 produces a homogenous Lissajous pattern (such as Figs. 2A and Fig. 2B), and/or in the second operation mode, so that step S117 produces a homogenous Lissajous pattern (such as Figs. 2A and Fig. 2B). In the other operation mode, it is possible to provide a second type of more raster-like Lissajous pattern (such as e.g. in Figs. 3A and 3B), if desired.

[0218] Herein, in some exemplary embodiments, for example, if the first operation mode provides a homogenous Lissajous pattern type by similar or substantially similar resonance frequencies of the k-th normal mode of the first axis and the n-th normal mode of the second axis, an even more raster-like second type of Lissajous pattern can be provided in the second operation mode, if the axes are switched in opposite directions, e.g. if $k > i$ and $n < m$ or vice versa with $k < i$ and $n > m$.

[0219] In the above, the micromirror is assumed to be operated in both operation modes and switched between operation modes. In some further exemplary embodiments, it is possible to pre-select the default operation mode in a setup operation (e.g. in a setup operation which can be performed by the user at setup and/or when selecting a menu option enabling user-setup), see e.g. Fig. 16.

[0220] **Fig. 16** is a schematic flow chart exemplarily illustrating another method of operating a 2D micromirror 10 according to some further exemplary embodiments.

[0221] The method exemplarily comprises a step S121 of selecting an operation mode among different operation modes, such as the first and second operation modes discussed above (or more than two operation modes), wherein the operation modes are preferably user-selectable.

[0222] That is, at initial setup of the device and/or when the user activates an operation selection function in a user menu screen, the user can select the preferred operation mode. In some exemplary embodiments, the user can be shown images projected in different operation modes (e.g. in accordance with the above methods), and/or the user can select the desired operation mode among a displayed list of options in a menu screen.

[0223] Preferably, each of the user-selectable operation modes is associated with certain normal modes of the first and second axes.

[0224] Upon selection, the method can comprise a step S122 of driving the first axis of two axes of the 2D micromirror 10 in resonance substantially at a resonance frequency of the first axis of the 2D micromirror 10 according to the selected operation mode (e.g. associated with an n-th normal mode of the first axis; e.g. with even numbered n, such as n = 2, 4, 6, 8, or higher; or with odd numbered n, such as n = 1, 3, 5, 7, or higher), and a step S132 of driving the second axis of the two axes of the 2D micromirror 10 in resonance substantially at a resonance frequency of the second axis of the 2D micromirror 10 according to the selected operation mode (e.g. associated with an m-th normal mode of the second axis; e.g. with even numbered m, such as m = 2, 4, 6, 8, or higher; or with odd numbered m, such as m = 1, 3, 5, 7, or higher; with m being different than n).

[0225] Accordingly, by reflecting a light beam on the oscillating mirror of the micromirror 10 driven according to S122 and S123, the 2D-driven oscillations in the first and second axes of the micromirror 10 are suitable to produce a Lissajous pattern of a user-selected type based on the selected operation mode, if m and n are selected even numbered, which projected Lissajous pattern can preferably be different from the Lissajous patterns of the non-selected operation modes; see e.g. step S124 of projecting or scanning according to a Lissajous pattern associated with the selected operation mode, when the micromirror is driven in the selected operation mode. Alternatively, if n and/or m are odd-numbered, an interferometry application can be performed in one or both selectable operation modes.

[0226] In the above, exemplary embodiments have been described, advantageously allowing to operate micromirrors in different operation modes, which, in some exemplary aspects, allows to provide different Lissajous patterns for different user preferences and/or different applications, while allowing to operate the different two or more operation modes still very efficiently in that both axes can be resonant-operated in each of the two or more operation modes, this allowing to avoid the significantly less efficient utilization of quasi-static operation. In other exemplary embodiments, this concept can be applied also to interferometry applications and/or 1D scanning operations (e.g. for bar code scanning).

[0227] While certain exemplary embodiments have been described above and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative of and are not restrictive on the broad disclosure, and that the exemplary embodiments of disclosure are not limited to the specific constructions and arrangements shown and described, since various other changes, combinations, omissions, modifications and substitutions, in addition to those set forth in the above paragraphs, are possible. Those skilled in the art will appreciate that various adaptations, modifications, and/or combination of the just described embodiments can be configured without departing from the scope of the disclosure. Therefore, it is to be understood that, within the scope of the appended claims, the disclosure may be practiced other than as specifically described herein. For example, unless expressly stated otherwise, the steps of processes described herein may be performed in orders different from those described herein and one or more steps may be combined, split, or performed simultaneously. Those skilled in the art will also appreciate, in view of this disclosure, that different embodiments of the disclosure described herein may be combined to form other embodiments of the disclosure.

Claims

1. Method for operating a micromirror device (10), the micromirror device (10) comprising a mirror (300) configured to be driven to oscillate with respect to at least a first axis (A1; A2), the method comprising:

- selecting an operation mode among at least two selectable operation modes of the micromirror device (10), wherein

  a first operation mode of the at least two selectable operation modes is associated with oscillation of the mirror (300) substantially at a resonance frequency of a transverse normal mode of oscillation of the mirror (300) associated with the first axis (A1; A2), and

  a second operation mode of the at least two selectable operation modes is associated with oscillation of the mirror (300) substantially at a resonance frequency of another transverse normal mode of oscillation of the mirror (300) associated with the first axis (A1; A2); and

- driving the oscillation of the mirror (300) according to the selected operation mode.

2. The method according to claim 1, further comprising:

driving, when the first operation mode is selected, the oscillation of the mirror (300) according to the selected first operation mode substantially at the resonance frequency associated with an N-th transverse normal mode of oscillation of the mirror (300) associated with the first axis (A1; A2); and/or

driving, when the second operation mode is selected, the oscillation of the mirror (300) according to the selected second operation mode substantially at the resonance frequency of another M-th transverse normal mode of oscillation of the mirror (300) associated with the first axis (A1; A2).

3. The method according to claim 1 or 2, wherein

the respective transverse normal mode of the selected operation mode is an even-numbered transverse normal mode associated with the first axis (A1; A2), and
the oscillation of the mirror (300) is driven according to the selected operation mode for performing a projection or scanning operation of the micromirror device (10) utilizing a light beam being reflected on the oscillating mirror.

4. The method according to claim 1 or 2, wherein

the respective transverse normal mode of the selected operation mode is an odd-numbered transverse normal mode associated with the first axis (A1; A2), and
the oscillation of the mirror (300) is driven according to the selected operation mode for performing an interferometry operation of the micromirror device (10) utilizing a light beam being reflected on the oscillating mirror.

5. The method according to at least one of the preceding claims, wherein
selecting the operation mode comprises switching between the first operation mode and the second operation mode.

6. The method according to claim 5, wherein
the respective transverse normal modes of the first and second operation modes are different even-numbered transverse normal modes associated with the first axis (A1; A2), and switching between the first operation mode and the second operation mode switches between two operation modes for performing resonant-operated projection or scanning operations of the micromirror device (10) at different respective resonant frequencies associated with the first axis (A1; A2).

7. The method according to claim 5, wherein

the respective transverse normal modes of the first and second operation modes are different odd-numbered transverse normal modes associated with the first axis (A1; A2), and switching between the first operation mode and the second operation mode switches between two operation modes for performing resonant-operated interferometry operations of the micromirror device (10) at different respective resonant frequencies associated with the first axis (A1; A2); or
the respective transverse normal mode of the first operation mode is an even-numbered transverse normal mode, and the respective transverse normal mode of the second operation mode is an odd-numbered transverse normal mode, and switching between the first operation mode and the second operation mode switches between an operation mode for performing a resonant-operated projection or scanning operation of the micromirror device (10) and an operation mode for performing a resonant-operated interferometry operation of the micromirror device (10).

8. The method according to at least one of the preceding claims, wherein

the mirror (300) is configured to be driven to oscillate in two dimensions with respect to the first axis (A1) and a second axis (A2), and
driving the oscillation of the mirror (300) according to the selected operation mode includes driving a substantially resonant oscillation of the mirror (300) with respect to the first axis (A1) and driving a substantially resonant oscillation of the mirror (300) with respect to the second axis (A2).

9. The method according to claim 8, wherein

the first operation mode is associated with a tilt oscillation of the mirror (300) about the second axis (A2) driven substantially at the resonance frequency of an even-numbered N-th transverse normal mode of oscillation of the mirror (300) with respect to the first axis (A1), and
the second operation mode is associated with a tilt oscillation of the mirror (300) about the second axis (A2) driven substantially at the resonance frequency of another even-numbered M-th normal mode of oscillation of the mirror (300) with respect to the first axis (A1).

10. The method according to claim 9, further comprising

generating a Lissajous scan or projection pattern by reflecting a light beam on the mirror (300), while driving the oscillation of the mirror (300) about the first axis (A1) substantially at a resonance frequency of oscillation of the mirror (300) about the first axis (A1) and driving the oscillation of the mirror (300) about the second axis (A2) according to the selected operation mode,
wherein a first type of Lissajous pattern is generated in the first operation mode and a second type of Lissajous pattern is generated in the second operation mode.

11. The method according to at least one of claims 8 to 10, wherein
a first ratio between the resonance frequency of oscillation of the mirror (300) about the first axis (A1) and the respective resonance frequency of oscillation of the mirror (300) about the second axis (A2) according to the first operation mode is substantially equal or larger than 1:1.2 and/or substantially equal or smaller than 1: 0.8, in particular substantially equal or larger than 1:1.1 and/or substantially equal or smaller than 1: 0.9, and preferably the first ratio is substantially 1:1.

12. The method according to at least one of claims 8 to 11, wherein
a second ratio between the resonance frequency of oscillation of the mirror (300) about the first axis (A1) and the respective resonance frequency of oscillation of the mirror (300) about the second axis (A2) according to the second operation mode is substantially equal or smaller than 1: 2, in particular substantially equal or smaller than 1: 3 and preferably the second ratio is substantially equal or smaller than 1: 5; and/or the second ratio is substantially equal or larger than 1: 20 and preferably the second ratio is substantially equal or larger than 1:10.

13. The method according to at least one of claims 8 to 12, further comprising:

driving the oscillation of the mirror (300) about the second axis (A2) according to the first operation mode substantially at the resonance frequency of the N-th normal mode of oscillation of the mirror (300) about the second axis (A2) and/or driving the oscillation of the mirror (300) about the second axis (A2) according to the second operation mode substantially at the resonance frequency of the M-th normal mode of oscillation of the mirror (300) about the second axis (A2);
wherein driving the oscillation of the mirror (300) about the first axis (A1) according to the first operation mode and the second operation mode is performed substantially at the same resonance frequency of a transverse normal mode of oscillation of the mirror (300) about the first axis (A1) with respect to the second axis (A2); or
wherein driving the oscillation of the mirror (300) about the first axis (A1) according to the first operation mode and driving the oscillation of the mirror (300) about the first axis (A1) according to the second operation mode is performed substantially at different resonance frequencies of different even-numbered transverse normal mode of oscillation of the mirror (300) about the first axis (A1) with respect to the second axis (A2).

14. Apparatus for operating a micromirror device (10), comprising:
the micromirror device (10) comprising a mirror (300) configured to be driven to oscillate with respect to at least a first axis (A1; A2), and a controller (30) configured to control operating the micromirror device (10) according to the method of at least one of the preceding claims.

15. Computer program means comprising instructions which, when the program is executed by a controller of an apparatus for operating a micromirror device (10), the micromirror device (10) comprising a mirror (300) configured to be driven to oscillate with respect to at least a first axis (A1; A2), cause the controller to carry out the method of at least one of claims 1 to 13.

Fig. 1

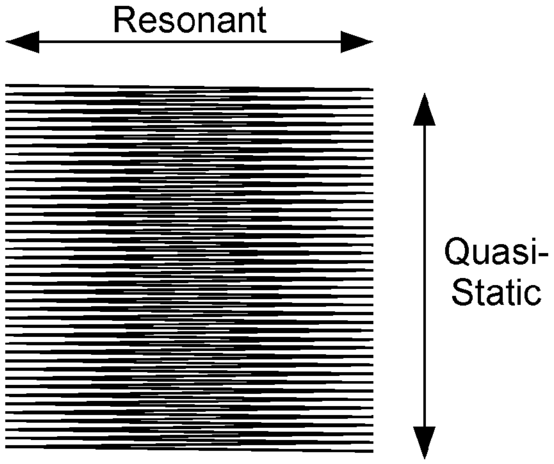

Fig. 2A

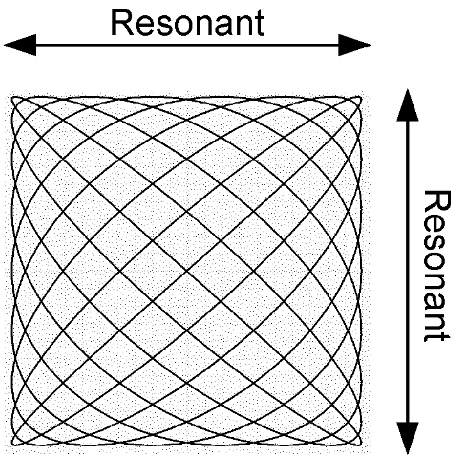

Fig. 2B

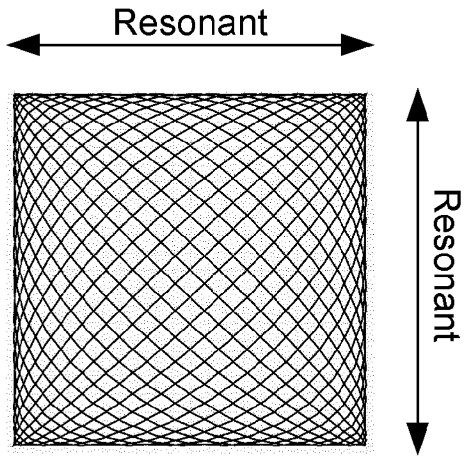

Fig. 3A

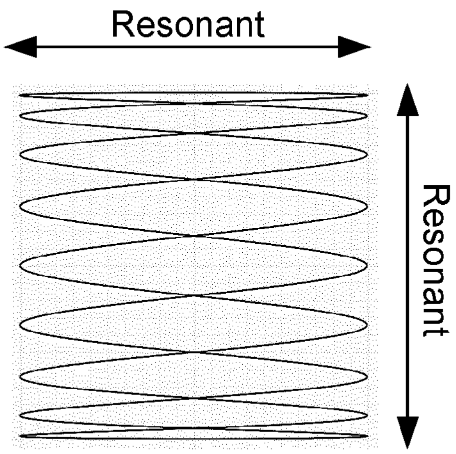

Fig. 3B

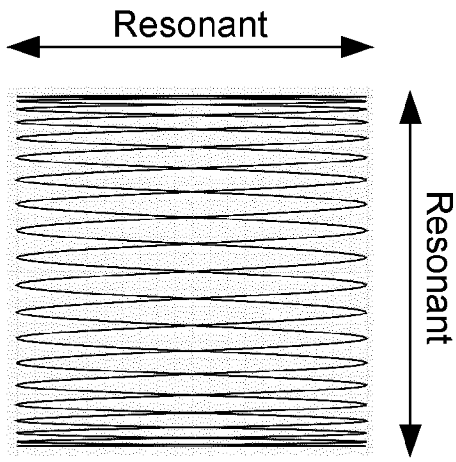

Fig. 4

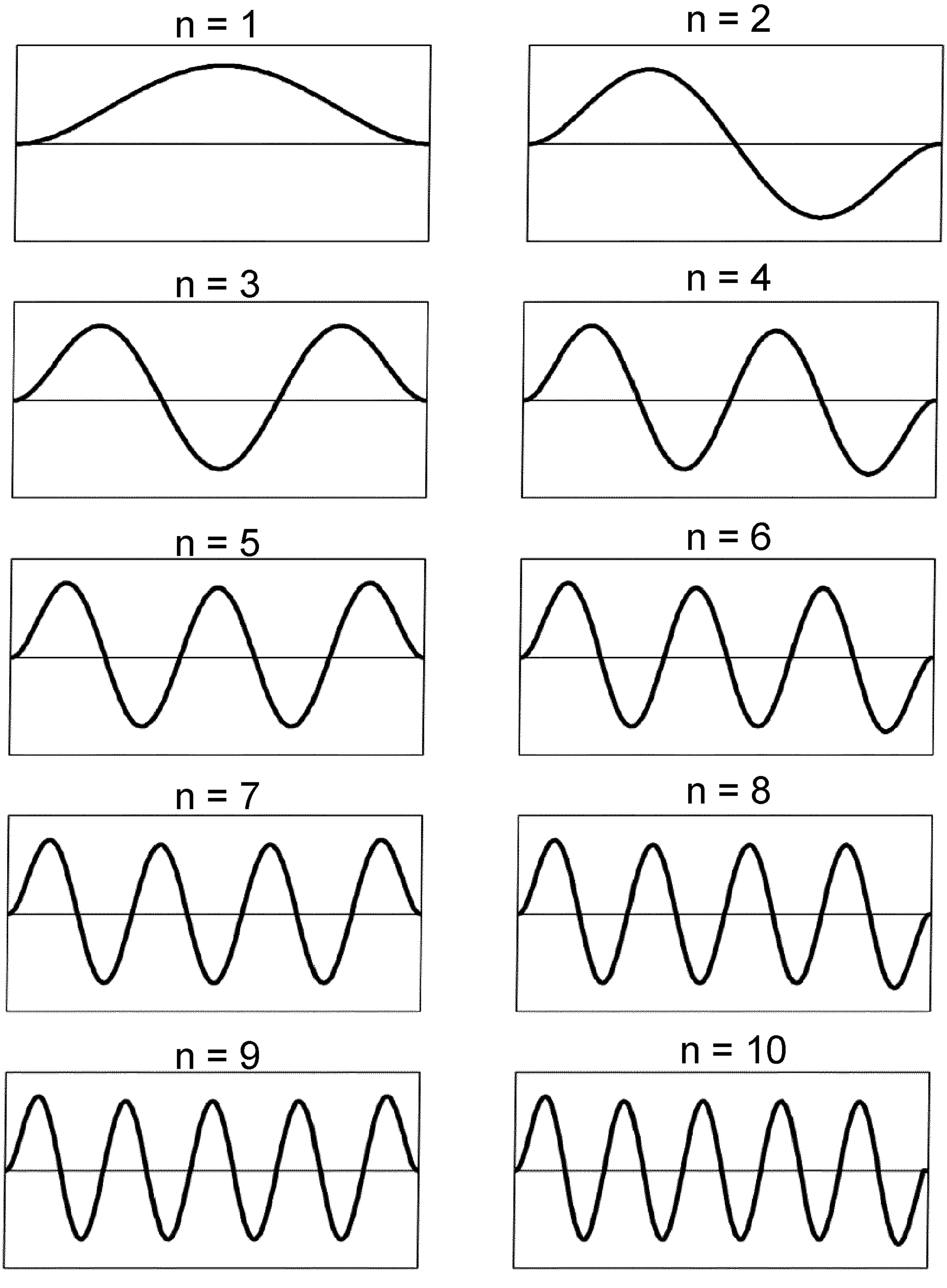

Fig. 5

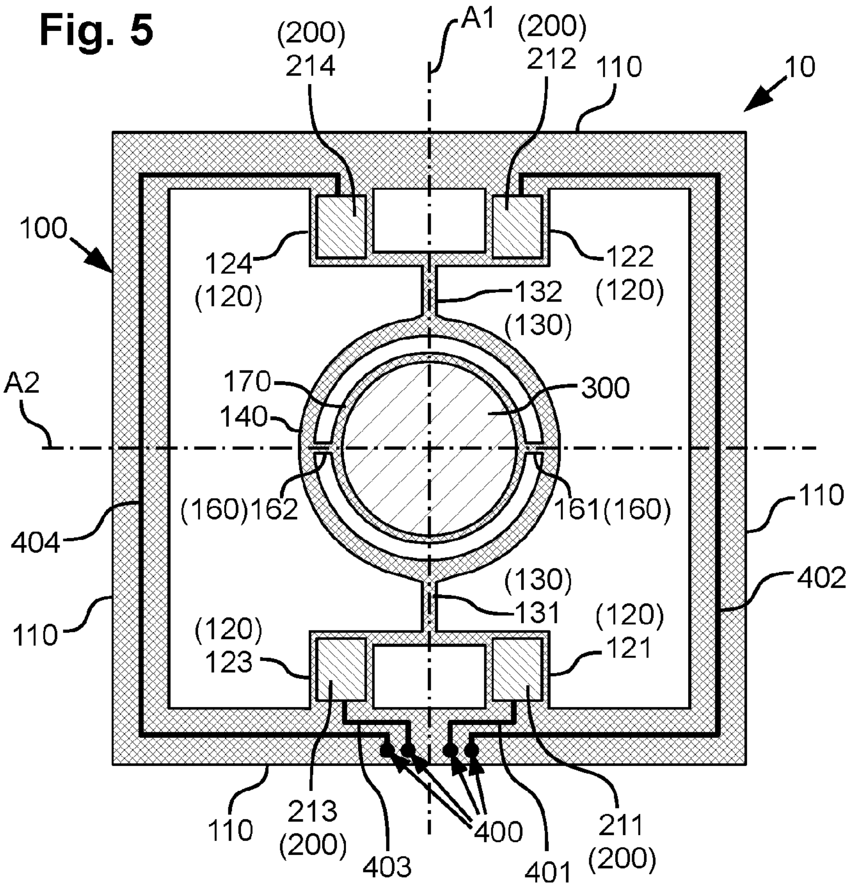

Fig. 6

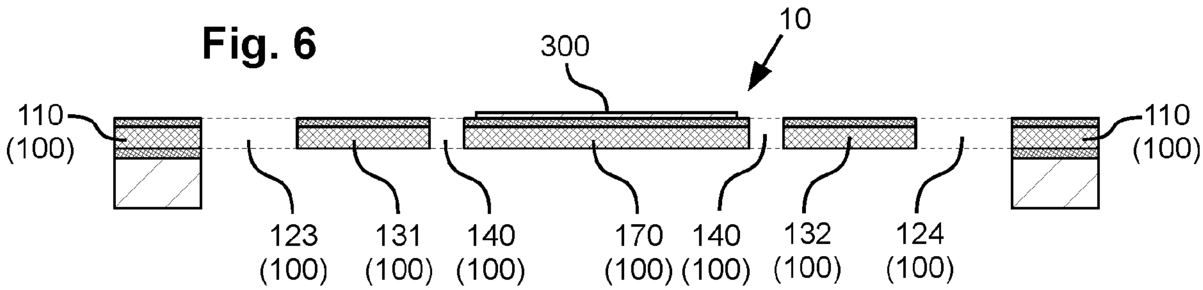

Fig. 7

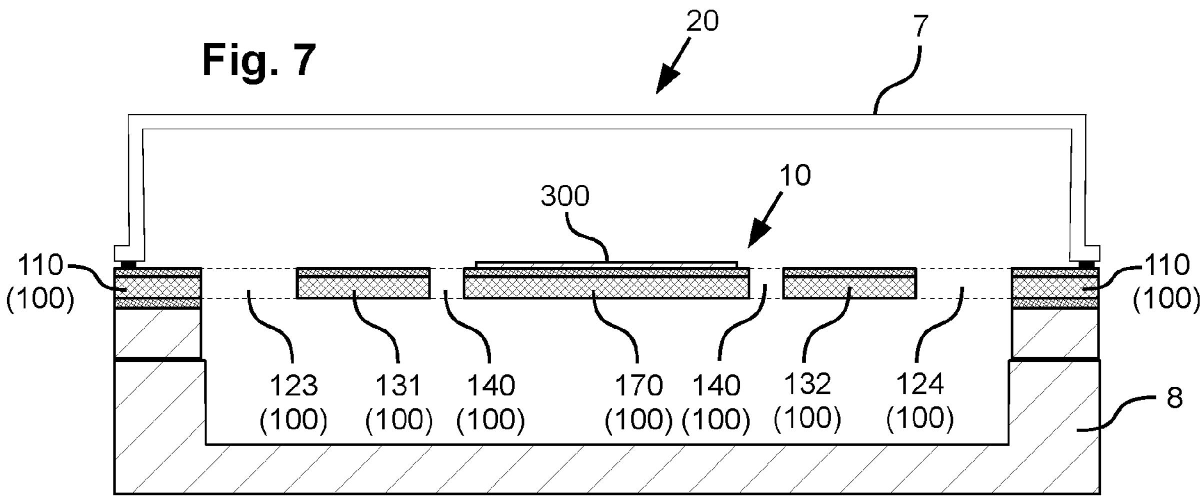

Fig. 8A

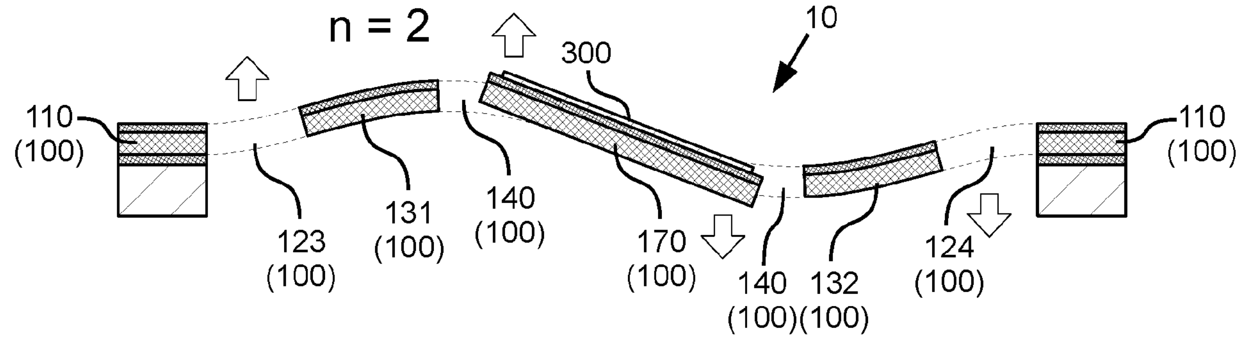

Fig. 8B

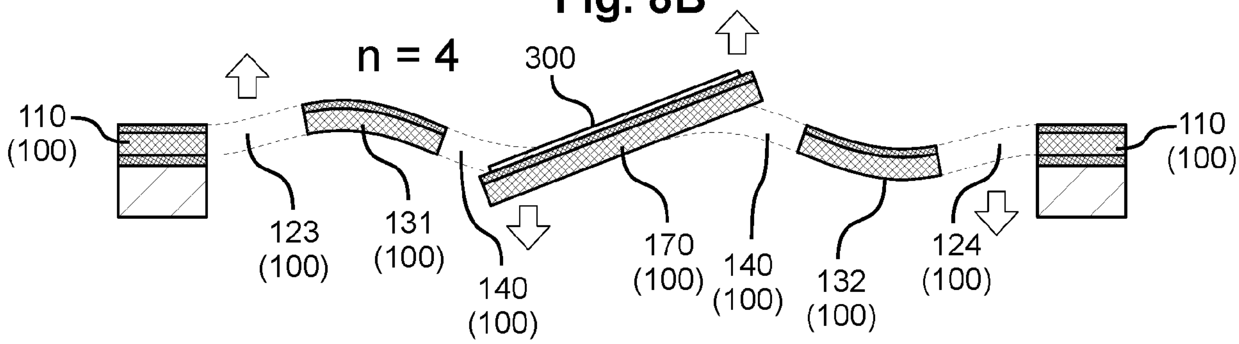

Fig. 8C

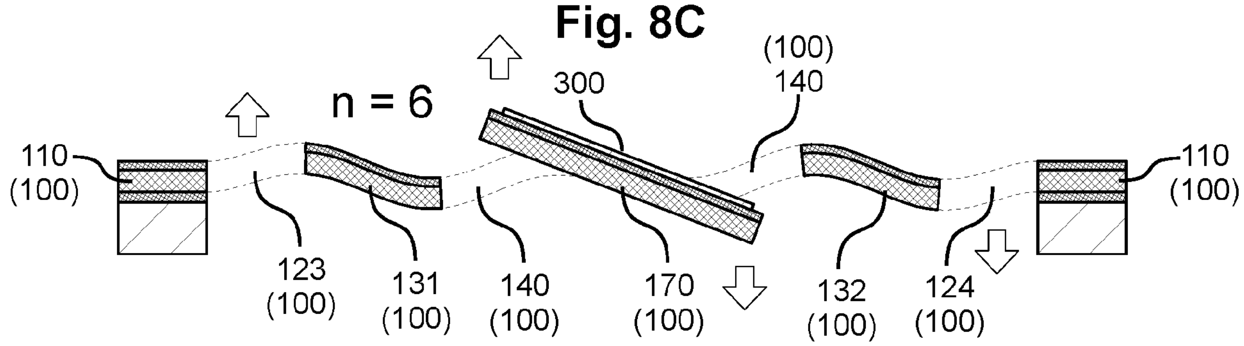

Fig. 8D

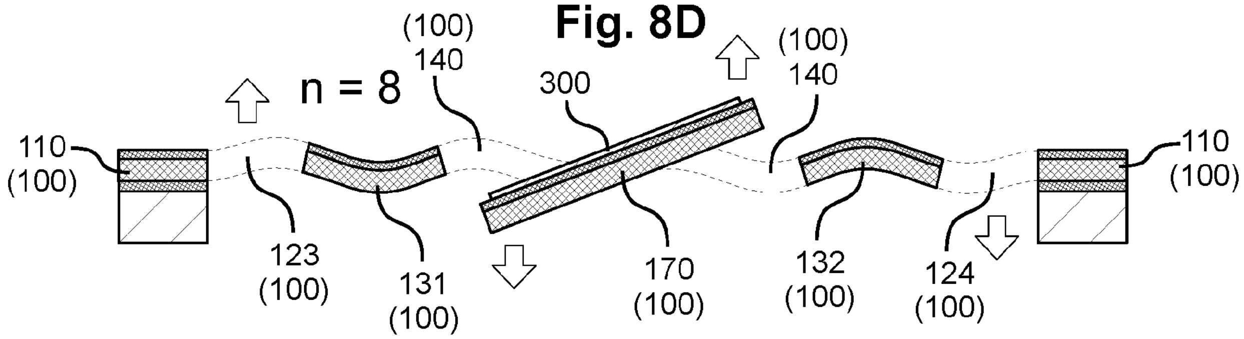

Fig. 9A

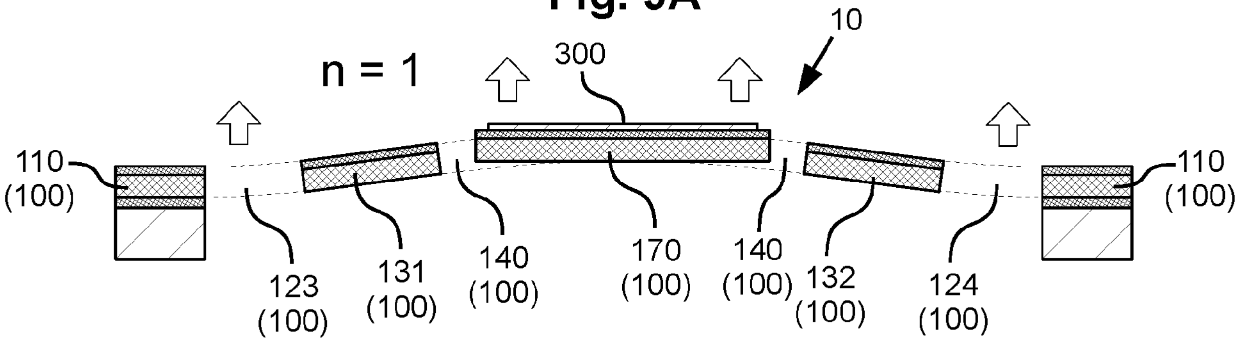

Fig. 9B

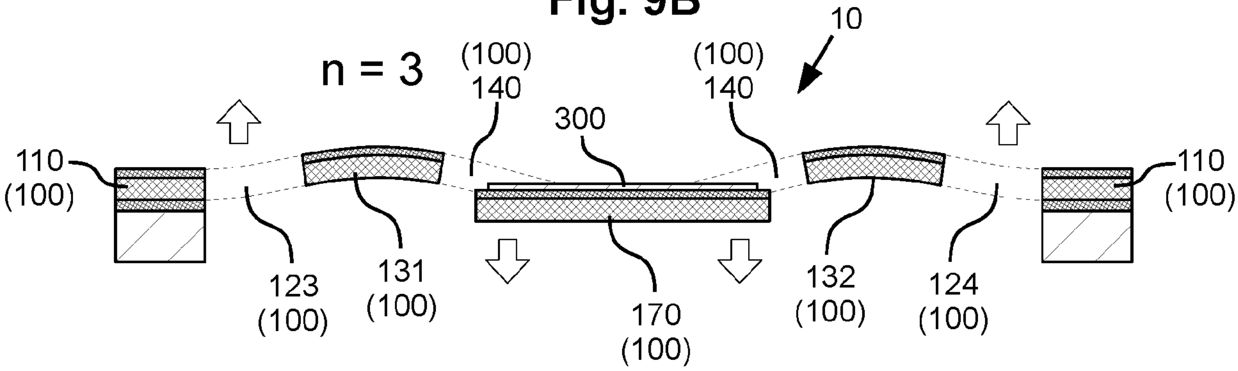

Fig. 9C

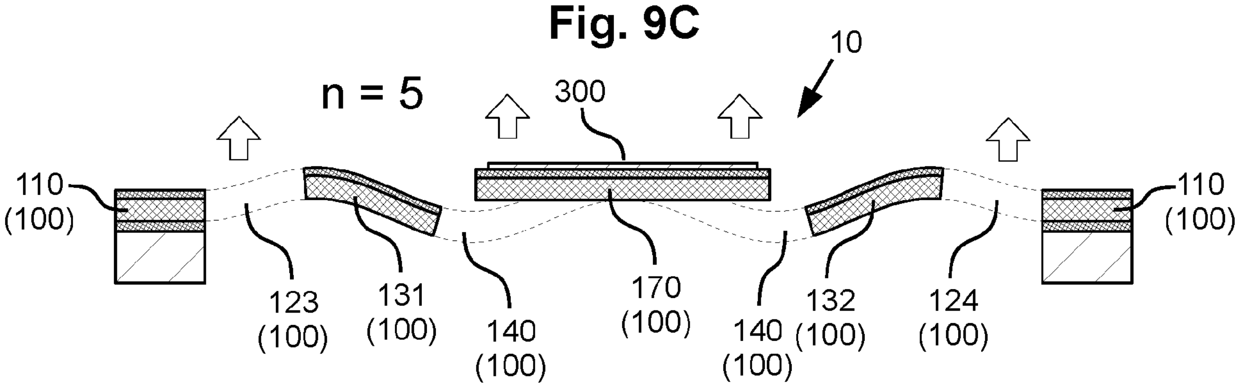

Fig. 10

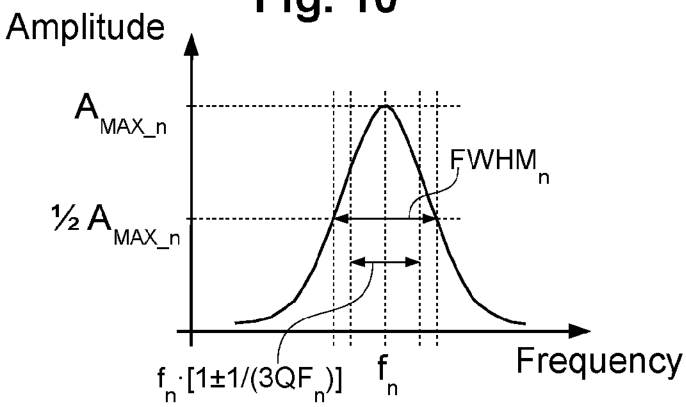

Fig. 11

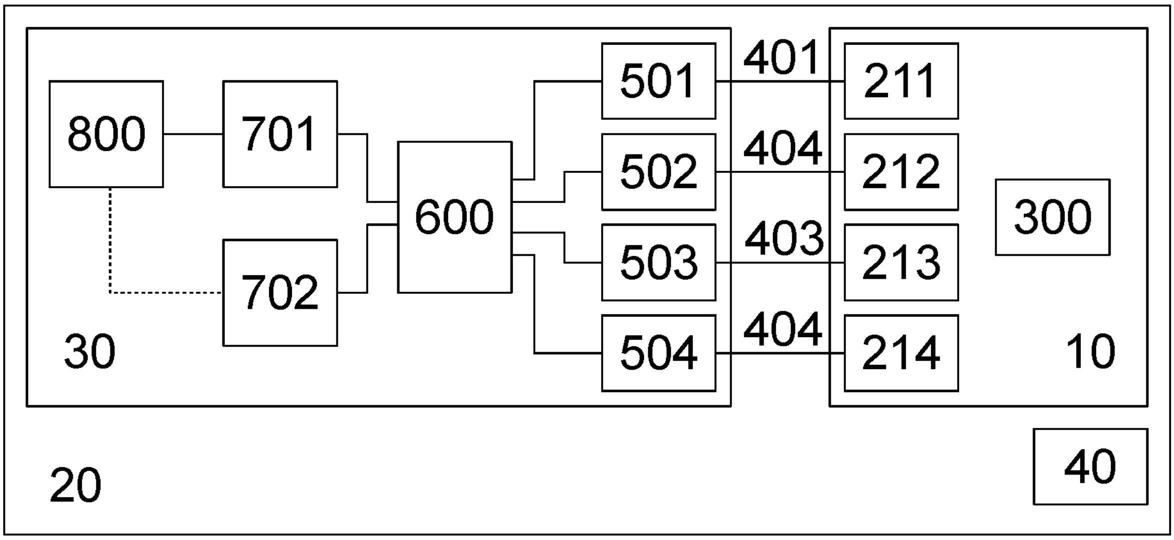
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Fig. 12

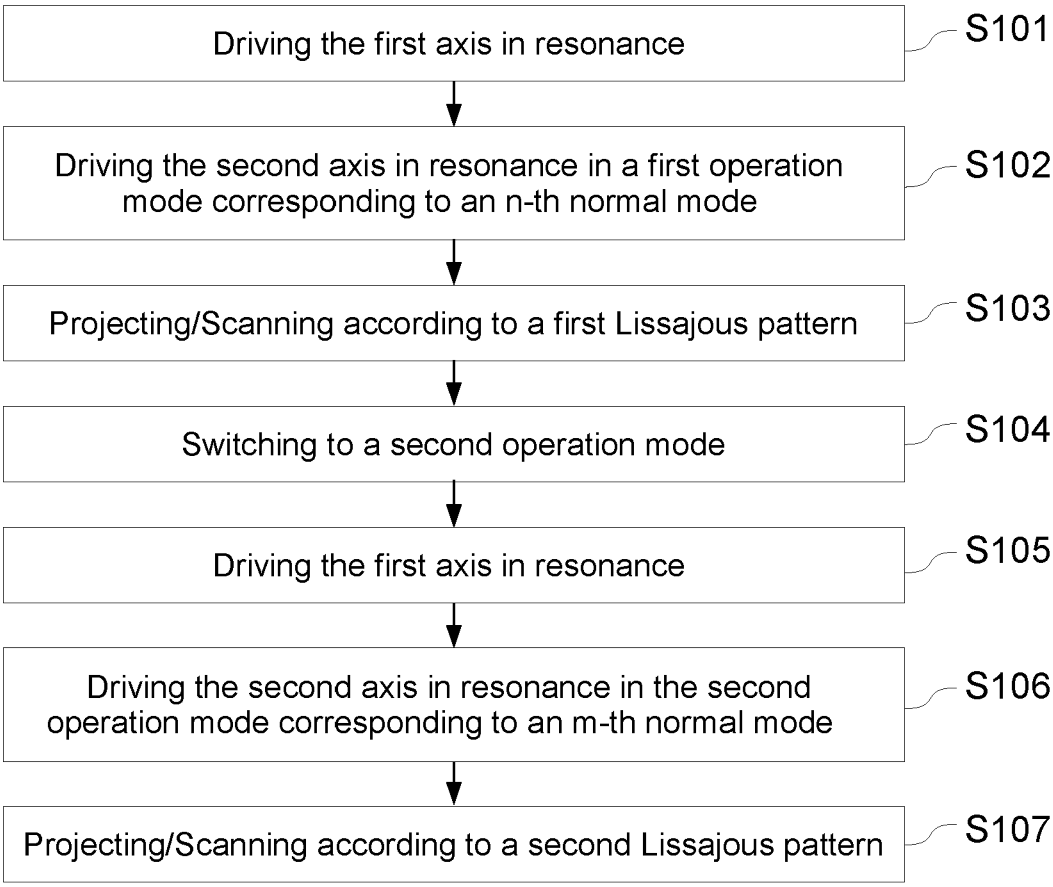

Driving the first axis in resonance
S101
Driving the second axis in resonance in a first operation mode corresponding to an n-th normal mode
S102
Projecting/Scanning according to a first Lissajous pattern
S103
Switching to a second operation mode
S104
Driving the first axis in resonance
S105
Driving the second axis in resonance in the second operation mode corresponding to an m-th normal mode
S106
Projecting/Scanning according to a second Lissajous pattern
S107

Fig. 13

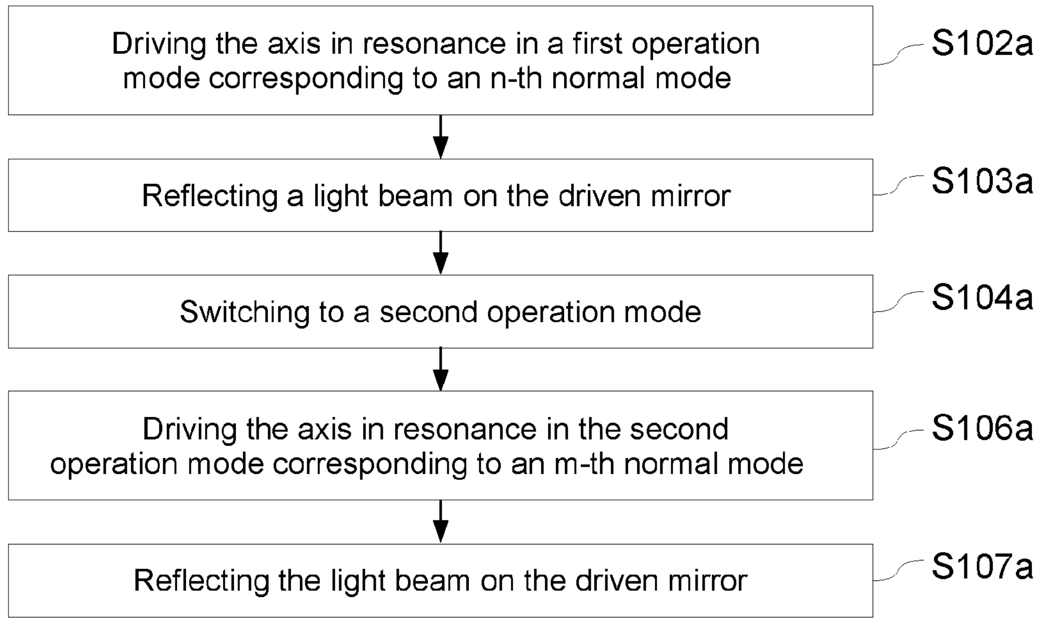
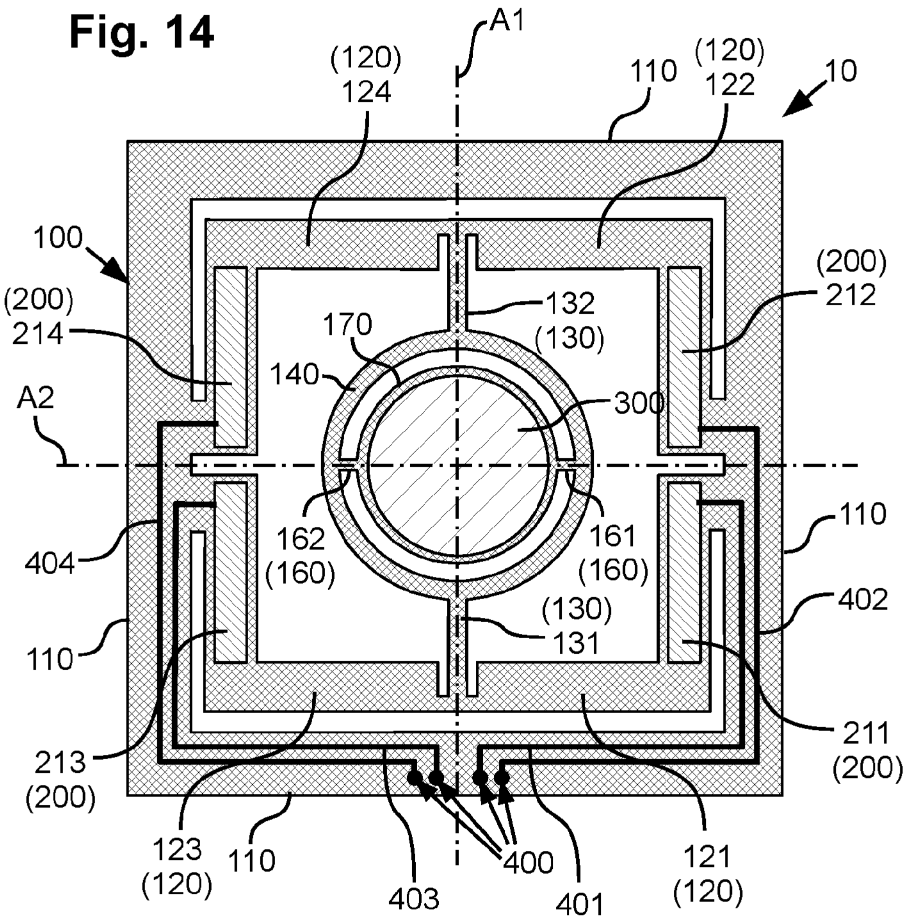

Driving the axis in resonance in a first operation mode corresponding to an n-th normal mode
S102a
Reflecting a light beam on the driven mirror
S103a
Switching to a second operation mode
S104a
Driving the axis in resonance in the second operation mode corresponding to an m-th normal mode
S106a
Reflecting the light beam on the driven mirror
S107a

Fig. 14


A1
(120)
124
110
(120)
122
10
100
(200)
212
(200)
214
170
132
(130)
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A2
300
404
162
(160)
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(160)
110
402
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(130)
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(200)
211
(200)
123
(120)
110
403
400
401
121
(120)

Fig. 15

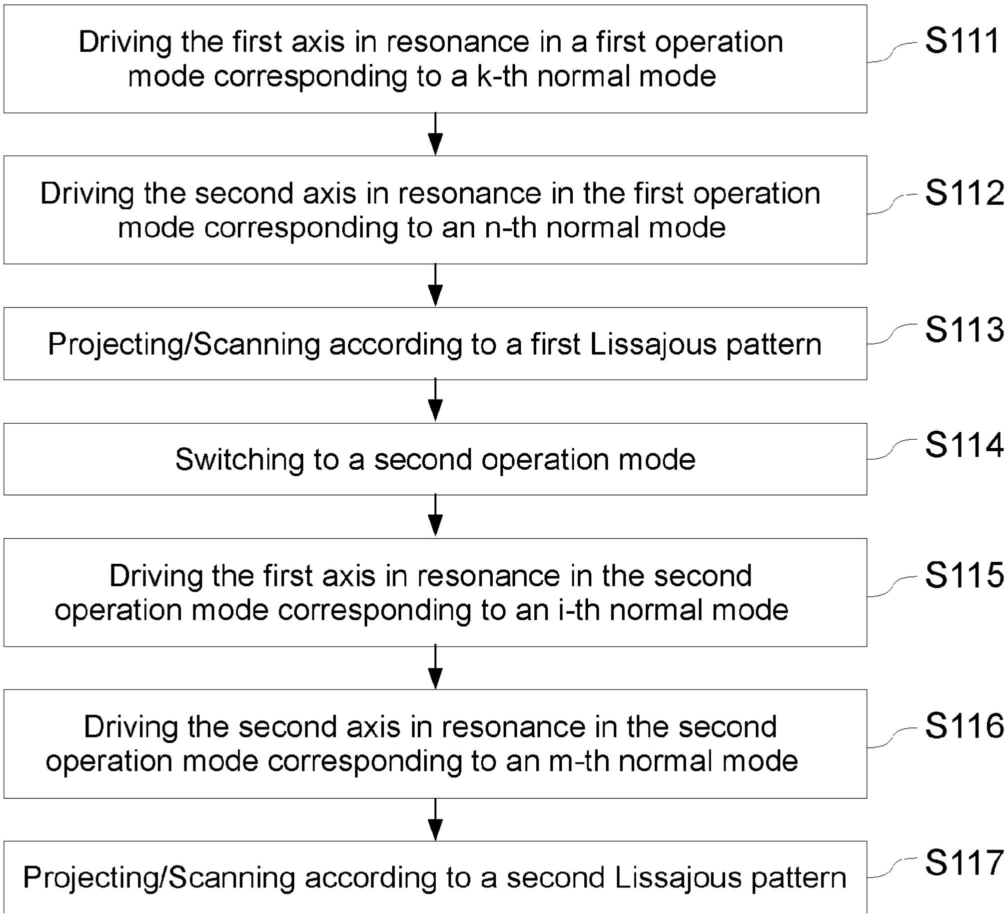
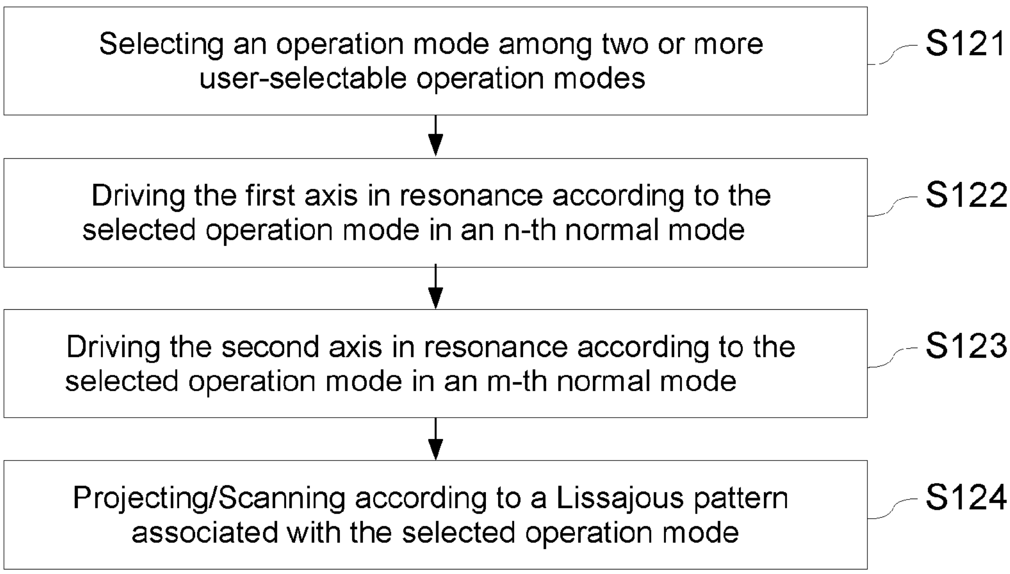

Driving the first axis in resonance in a first operation mode corresponding to a k-th normal mode
S111
Driving the second axis in resonance in the first operation mode corresponding to an n-th normal mode
S112
Projecting/Scanning according to a first Lissajous pattern
S113
Switching to a second operation mode
S114
Driving the first axis in resonance in the second operation mode corresponding to an i-th normal mode
S115
Driving the second axis in resonance in the second operation mode corresponding to an m-th normal mode
S116
Projecting/Scanning according to a second Lissajous pattern
S117

Fig. 16


Selecting an operation mode among two or more user-selectable operation modes
S121
Driving the first axis in resonance according to the selected operation mode in an n-th normal mode
S122
Driving the second axis in resonance according to the selected operation mode in an m-th normal mode
S123
Projecting/Scanning according to a Lissajous pattern associated with the selected operation mode
S124

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EUROPEAN SEARCH REPORT

Application Number
EP 23 19 4292

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 2023/194855 A1 (NAONO TAKAYUKI [JP] ET AL) 22 June 2023 (2023-06-22) * paragraph [0053] - paragraph [0159]; figures 1-29c * -----	1-11, 13-15	INV. G09G3/02
X	US 2019/064508 A1 (TORKKELI ALTTI [FI] ET AL) 28 February 2019 (2019-02-28) * paragraph [0022] - paragraph [0058]; figures 1-10 * -----	1-10,12, 14,15	

TECHNICAL FIELDS SEARCHED (IPC)

G09G

1

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	9 February 2024	Harke, Michael

CATEGORY OF CITED DOCUMENTS

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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 23 19 4292

09-02-2024

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- **Y. LIU et al.** AlScN Piezoelectric MEMS Mirrors with Large Field of View for LiDAR Application. *Micromachines*, 18 September 2022, vol. 13, 1550 **[0004]**
- **S. GU-STOPPEL**. Entwicklung, Herstellung und Charakterisierung piezoelektrischer Mikrospiegel'' (engl.: Development, Manufacture and Characterization of Piezoelectric Micromirrors. Books on Demand, 2016 **[0004]**