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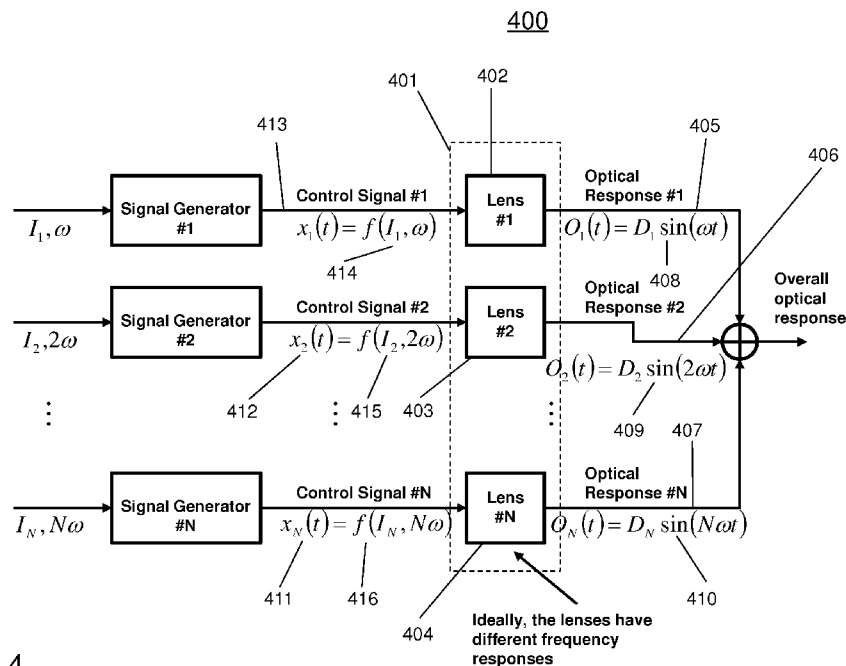


Fig. 4

(57) Abstract: The invention provides a focus tunable optical system, comprising a lens assembly including a plurality of focus tunable lenses, FTLs, coaxially disposed along an optical axis, each FTL contributing to an optical power of the lens assembly; and a controller configured to control the optical power of the lens assembly by applying to each FTL a respective control signal, thereby generating a periodic optical response of the respective FTL, wherein the optical response of each FTL is substantially different from the optical response of any other FTL of the plurality of FTLs.



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VARIFOCAL OPTICAL SYSTEM

TECHNICAL FIELD

5 The invention relates to a device and a method for controlling an assembly of focus tunable lenses (FTL). In particular, the purpose of the device and method is to enhance the optical response of a focus tunable optical system, e.g., a Multifocal Plane Display (MFD).

10 BACKGROUND

Multi-focal-plane near eye displays (MFD) have recently emerged as display devices (e.g., head-mounted displays) for volumetric 3D rendering. Volumetric 3D rendering can alleviate visual discomfort that may arise with some other types of near eye displays
15 (NEDs), e.g., with stereoscopic 3D displays which render depth perception of 3D scenes from pairs of 2D perspective images with binocular disparities presented at a fixed distance (focal plane) to the viewer. The fixed distance creates an unnatural viewing condition and causes a Vergence-Accommodation Conflict (VAC) with adverse consequences, such as visual discomfort, fatigue, or distorted depth perception.

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Multiple carefully placed, discrete focal planes divide an extended 3D scene volume into multiple zones along the visual axis. Virtual objects within a zone are rendered by the corresponding pair of adjacent focal planes such that the 2D perspective images of these objects are displayed at a nearly correct focal distance.

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MFD implementations can be categorized into spatially multiplexed or temporally/time multiplexed techniques. In the time multiplexed systems, the viewing distance of a single 2D display from the eye is rapidly switched in synchronization with the rendering of frames of multiple focal planes to create a flicker-free perception. In order to perform the
30 focal plane switching high-speed Focal Modulator Elements utilizing variable power lenses or focus tunable lenses are employed to continuously adjust and/or modulate the focal length (or, equivalently, the optical power) of, e.g., electrically tunable lens or deformable membrane mirror devices (DMMD). A focal modulator element may be

implemented in the form of a shape-changing lens. The lens may comprise a container, which is filled with an optical fluid and sealed off with, e.g., an elastic polymer membrane. An electrical current (e.g., flowing through a coil of an actuator of the lens) may be used to control the deflection of the lens and thus the focal distance of the lens. A plurality of optical power levels (and thus a corresponding plurality of focal planes, e.g., 4 focal planes) can be generated by applying a control signal (e.g., an electrical current) that takes the form of a step function, each value of the step function representing a corresponding current level and thus a corresponding optical power level.

10 However, a multi-focal display system of the above described kind may suffer from artifacts related to inertia of the Focal Modulator Elements, e.g., as illustrated in FIG. 2. An example of lens inertia is highlighted in “*Datasheet: EL-10-30-Series, Fast Electrically Tunable Lens, Optotune, Jan 2017*”. Due to lens inertia, an oscillation artifact (notably, overshoot and ringing) may appear in the optical response. The oscillation artifact may be characterized by a rise time and a settling time. This can produce a delay before the optical system reaches its steady-state period. This, in turn, may limit the maximum frame rate that can be achieved.

The problem may be alleviated by pre-processing or pre-compensating the control signal, to enhance the optical response of the variable optical power lense, e.g., as highlighted in “*Datasheet: EL-10-30-Series, Fast Electrically Tunable Lens, Optotune, Jan 2017*”. More specifically, a shorter settling time may be achieved by removing resonant frequencies from the applied step function and by applying an overshooting step function.

25 SUMMARY

The invention aims at improving the image rendering quality of an MFD system. The invention specifically aims at reducing the undesired effects of artifacts arising from lens inertia in an optical system.

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The object of the invention is achieved by the solution defined in the enclosed independent claims. Advantageous implementations of the invention are further defined in the dependent claims.

An optical system of multiple closely cascaded FTLs is provided. The FTLs, e.g., electrically controlled liquid lenses, are placed separately and coaxially along an optical axis of an optical system. An improved optical step response is obtained by combining several optical responses produced by several FTLs, based on a Fourier decomposition of the desired ideal optical step response.

A first aspect of the invention provides a focus tunable optical system, comprising a lens assembly including a plurality of focus tunable lenses, FTLs, coaxially disposed along an optical axis, each FTL contributing to an optical power of the lens assembly, and a controller configured to control the optical power of the lens assembly by applying to each FTL a respective control signal, thereby generating a periodic optical response of the respective FTL, wherein the optical response of each FTL is substantially different from the optical response of any other FTL of the plurality of FTLs.

The different periodic optical responses of the FTLs lead to an improved total optical response of the lens assembly with less oscillation artifacts. For example, based on the Fourier decomposition of an ideal optical step response, an optical system of multiple FTLs can be constructed, whereby each FTL's optical response is a periodic function which corresponds to one or more Fourier components of the ideal optical step response. The sum of the Fourier components is the desired optical step response.

Each control signal applied by the controller to each respective FTL may be a sinusoidal signal, a periodic sequence of pulses, a periodic staircase function, or a periodic saw tooth function, depending, for instance, on the number of Fourier components of the ideal optical step response one of the plurality of FTLs needs to reproduce. The optical power of the lens assembly, or any FTL in the lens assembly for that matter, is considered as a function of time and is referred to herein as the optical response. The statement that the optical response of an FTL is substantially different from that of any other FTL means that the two optical responses differ in a non-trivial manner, that is, they do not differ merely by an overall amplitude scaling factor or by a time shift.

In an implementation form of the first aspect, the optical response of an FTL comprises a natural frequency of the FTL.

In a further implementation form of the first aspect, the optical response of an FTL comprises a frequency lower than the natural frequency of the FTL.

5 The control signal for any FTL can generally be a periodic signal with a specific amplitude, frequency and phase lag. The control signal parameters current intensity, frequency and phase can be derived knowing the expected optical response. Driving an FTL at below its natural frequency (resonant frequency) has the advantage that only a low intensity (the lowest possible) is required and the phase shift is reduced.

10 In a further implementation form of the first aspect, the controller is configured to perform a Fourier analysis of a desired optical response and to generate for each or one or more of the FTLs the respective control signal in proportion to the sum of one or more Fourier components of the desired optical response.

15 In a further implementation form of the first aspect, each or one or more of the FTLs the optical response of the respective FTL comprises one or more Fourier components of the optical response of the lens assembly.

20 Due to practical constraints a limited number of FTLs may be disposed in an MFD to produce an optical response comprising a larger number of Fourier components. Subsequently the control signal for each FTL needs to take account of this and drive the FTL in proportion to the sum of one or more Fourier components of the optical response of the lens assembly.

25 In a further implementation form of the first aspect, the optical response of one of the FTLs comprises the lowest Fourier component of the optical response of the lens assembly (that is, the Fourier component with the lowest frequency).

30 In a further implementation form of the first aspect, for each or one or more of the FTLs the optical response of the respective FTL comprises only odd Fourier components or only even Fourier components of the optical response of the lens assembly.

In a further implementation form of the first aspect, for each or one or more of the FTLs the optical response of the respective FTL comprises less than 10, preferably less than 5, Fourier components of the optical response of the lens assembly.

5 In a further implementation form of the first aspect, the plurality of FTLs comprises a first, a second, and a third FTL, the optical response of the first FTL approximates a first sum of a number of Fourier components of the desired optical response of the lens assembly, the optical response of the second FTL approximates a second sum of a subset of the remainder of the Fourier components of the desired optical response of the lens
10 assembly to compensate for a first residual of the first FTL, the optical response of the third FTL approximates a third sum of the remaining Fourier components of the desired optical response of the lens assembly to compensate for a second residual of the second FTL, and the sum of the optical responses of the first, the second and the third FTLs approximates the desired optical response.

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Above embodiments provide different ways of distributing the Fourier components of the optical response of the lens assembly over a limited number of FTLs.

In a further implementation form of the first aspect, the optical response of the lens
20 assembly is a periodic staircase function or an approximation of a periodic staircase function.

A second aspect of the invention provides a multifocal display device, comprising a focus tunable optical system according to the first aspect or any of the implementation forms of
25 the first aspect.

A third aspect of the invention provides a method for controlling a focus tunable optical system, comprising the steps of controlling an optical power of a lens assembly, which comprises a plurality of focus tunable lenses, FTLs, coaxially disposed along an optical
30 axis of the lens assembly; and applying to each FTL a respective control signal, thereby generating a periodic optical response of the respective FTL, wherein the optical response of each FTL contributes to the optical power of the lens assembly and is substantially different from the optical response from any other FTL of the plurality of FTLs.

In an implementation form of the third aspect, the optical response of an FTL comprises a natural frequency of the FTL.

5 In a further implementation form of the third aspect, the optical response of an FTL comprises a frequency lower than the natural frequency of the FTL.

In a further implementation form of the third aspect, the method comprises performing a Fourier analysis of a desired optical response and generating for each or one or more of the FTLs the respective control signal in proportion to the sum of one or more Fourier
10 components of the desired optical response.

In a further implementation form of the third aspect, each or one or more of the FTLs the optical response of the respective FTL comprises one or more Fourier components of the optical response of the lens assembly.
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In a further implementation form of the third aspect, the optical response of one of the FTLs comprises the lowest Fourier component of the optical response of the lens assembly.

20 In a further implementation form of the third aspect, for each or one or more of the FTLs the optical response of the respective FTL comprises only odd Fourier components or only even Fourier components of the optical response of the lens assembly.

In a further implementation form of the third aspect, for each or one or more of the FTLs
25 the optical response of the respective FTL comprises less than 10, preferably less than 5, Fourier components of the optical response of the lens assembly.

In a further implementation form of the third aspect, the plurality of FTLs comprises a first, a second, and a third FTL, the optical response of the first FTL approximates a first
30 sum of a number of Fourier components of the desired optical response of the lens assembly, the optical response of the second FTL approximates a second sum of a subset of the remainder of the Fourier components of the desired optical response of the lens assembly to compensate for a first residual of the first FTL, the optical response of the

third FTL approximates a third sum of the remaining Fourier components of the desired optical response of the lens assembly to compensate for a second residual of the second FTL, and the sum of the optical responses of the first, the second and the third FTLs approximates the desired optical response.

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In a further implementation form of the third aspect, the optical response of the lens assembly is a periodic staircase function or an approximation of a periodic staircase function.

10 The method of the third aspect achieves all advantages and effects described above for the system of the first aspect.

A forth aspect of the invention provides a method for controlling a focus tunable
Computer program product comprising a program code for controlling a focus tunable
15 optical system according to the first aspect or any implementation form thereof or a multifocal display device according to the second aspect.

Accordingly, with the computer program product of the forth aspect, the advantages and effects described for the device of the first or the second aspect can be achieved.

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All devices, elements, units and means described in the present application could be implemented in the software or hardware elements or any kind of combination thereof. All steps which are performed by the various entities described in the present application as well as the functionalities described to be performed by the various entities are
25 intended to mean that the respective entity is adapted to or configured to perform the respective steps and functionalities. Even if, in the following description of specific embodiments, a specific functionality or step to be performed by external entities is not reflected in the description of a specific detailed element of that entity which performs that specific step or functionality, it should be clear for a skilled person that these
30 methods and functionalities can be implemented in respective software or hardware elements, or any kind of combination thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

The above described aspects and implementation forms of the invention will be explained in the following description of specific embodiments in relation to the enclosed drawings,
5 in which:

FIG. 1 shows an example of a multifocal display device.

FIG. 2 shows a control path of a multifocal display device.

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FIG. 3 shows an example of an optical staircase response of a lens assembly according to an embodiment of the invention.

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FIG. 4 shows an example of a lens assembly according to an embodiment of the present invention.

FIG. 5 shows an example of a signal path of an FTL according to an embodiment of the invention.

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FIG. 6 shows an example of a lens assembly of two FTLs according to an embodiment of the invention.

FIG. 7 shows an example of a lens assembly of three FTLs according to an embodiment of the invention.

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FIG. 8 shows an example of a method according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

30 Multifocal plane display (MFD) optical systems are related to Near eye displays (NED) or Near-to-eye (NTE) applications or devices. An example of such a device 100 is shown in FIG. 1. MFD implementations can be categorized into spatially multiplexed or temporally/time multiplexed techniques. In a time multiplexed system as shown for the

device 100 in FIG. 1, the viewing distance of a single 2D display from the eye is rapidly switched in synchronization with the rendering of frames of multiple focal planes to create a flicker-free perception. A key requirement of such a device 100 are ultrafast display elements 102 to sequentially display color images at a flicker fusion threshold speed (≥ 60 Hz frame rate), e.g. a Digital Micromirror Device (DMD) or Ferroelectric Liquid Crystal on Silicon (FLCoS). The next essential building blocks are high-speed focal modulator (or varifocal) elements 103 utilizing variable power lenses to continuously adjust or modulate the focal length or optical power, e.g. electrically tunable lenses or focus tunable lenses (FTL) and deformable membrane mirror devices (DMMD). MFD optical systems can provide a good balance between image quality and ease of implementation while alleviating VAC and enabling true volumetric 3D rendering.

The MFD device 100 shown in FIG. 2 comprises a Master Controller 101, Display Elements 102 and Focal Modulator Elements 103 for generating a focused image for 3D perception. The Master controller 101 produces a signal of a certain current intensity to control the Focal Modulator Elements 103. The Focal Modulator Elements 103 use focus tunable lenses (FTL), wherein the optical power of the FTLs is adjusted by said control signal. In order to generate several optical power levels (e.g., 4 such levels, corresponding to 4 focal planes), a control signal in the form of a step current is applied along a lens control function path. However, due to lens inertia a significant oscillation artifact (overshoot + ringing) appears in the optical response of the FTLs, which is characterized by certain periods of oscillating perturbations like rise and settling times, which occur in a step-up 104 or step-down 105 situation, when the optical power of the FTL needs to be increased 104 or decreased 103 by a certain amount in order to jump to a different focal plane. Depending on the physical properties of the FTL, the FTLs behave like a resonant circuit, which naturally exhibit characteristic resonance frequencies visible as peaks in the frequency spectrum 106 of a typical FTL.

Described below is an optical system of multiple, closely coaxially disposed and separately controlled FTLs, designed to remedy at least some of the shortcomings mentioned above. The optical system will suffer less from oscillation artifacts, as can be seen in Fig. 3, as each of the multiple FTLs is driven by a control signal comprising only a particular frequency of interest. In this example, each lens is driven with its proper

frequency (i.e. its free oscillation or fundamental frequency). This can be done by driving the FTL with a sinusoidal signal having a frequency equal to the fundamental frequency (i.e. the first harmonic) of the FTL. The combination of the optical responses of each of the sinusoidally driven FTLs then provides an ideal optical step response 303 or at least a
5 much improved approximation 301, 302 of the desired ideal step response 304 of the optical system by technically applying the principle of Fourier Series and the Harmonic Oscillator in combination with (multiple) cascaded FTLs. Ideally, based on the Fourier decomposition of the ideal optical step response an optical system of multiple FTLs can be constructed, whereby each FTL's optical response shall resemble a sinusoidal basis
10 function, which corresponds to each Fourier component. The sum of these Fourier components guarantees the generation or at least close approximation of the desired ideal optical step response.

An additional benefit of this arrangement lies in the fact that the undesirable delay of an optical system driven by instant changes of control signals can also be reduced. As a
15 consequence, faster focal scanning rates, higher frame rates or the ability to accommodate more focal planes can be achieved.

FIG. 3 shows the construction 300 of such an optical system according to an embodiment
20 of the invention by employing up to 32 Fourier components, which corresponds to 32 FTLs, in order to obtain an ideal 303 or at least a much improved approximated step response 301, 302. The required number of Fourier components can certainly be reduced by employing a better desired optical step response, e.g., by having a symmetric staircase function which reduces the needed number of high frequency components.

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FIG. 4 shows a block diagram 400 of a corresponding embodiment of such an optical system of multiple FTLs 401. Based on the principle of Fourier Series, any periodic signal (in this case the ideal step optical response) can be decomposed into a set of oscillating functions namely sinusoidal signals 408, 409, 410. The Fourier decomposition
30 gives a set of amplitudes D_j indicating optical power measured in diopter and frequencies $\omega_j = j \cdot \omega$, where $j=1, \dots, N$, whereby in this technical context the amplitude and the frequency is the amplitude and frequency of the optical response O_j 405, 406, 407 of each

FTL and frequency $j\omega$, whereby for illustrative purposes only “Lens #1” 402, “Lens #2” 403 and “Lens #N” 404 and their respective frequencies ω , 2ω and $N\omega$ are shown.

During the design process, a set of FTLs 402, 403, 404 may be chosen or manufactured to
 5 satisfy the requirement that each FTL has to yield an optical response 405, 406, 407, which oscillates at its respective frequency ω_j according to the given Fourier decomposition. This is highly related to the FTL’s properties (e.g., the diameter, fluid pump mechanism), which can be analyzed by its frequency response. Assuming, for example, differently sized FTLs, each FTL will then have a different frequency response
 10 and the desired control signal is decomposed so each FTL handles different frequency components (bigger FTLs handle lower frequency components, and vice versa). Knowing the frequency response of each FTL, a respective oscillating control signal 411, 412, 413 with frequency ω_j is generated. The frequency ω_j matches the fundamental frequency (also referred to herein as the lowest resonance or as the natural frequency) of the
 15 respective FTL, i.e. the lens is operated at resonance. Proper shaping of the FTL can thus be ensured. At higher resonances, the FTL will have an unwanted shape (not lens-like anymore). The current intensity I_j 414, 415, 416 may be further tuned to adjust the optical power D_j since both values are proportional to each other. In this embodiment it is assumed that the system delay is negligible or that there is a similar delay in each branch,
 20 which will easily be the case if each FTL is driven at its resonant frequency. This guarantees that the branches oscillate in phase with each other.

Alternatively, a compound lens comprising multiple FTLs can also be realized by considering that an FTL may be driven 501 by a frequency ω_j 506 other than its natural
 25 frequency η_j 510 as shown in Fig. 5. Considering an FTL as a Harmonic Oscillator 508 with a damping factor c_j 509 and a natural frequency η_j 510, the lens control signal 504 can generally be a periodic signal. The periodic control signal may oscillate with an amplitude I_j 505, a frequency ω_j 506 and a phase lag ϕ_j 507 between the control signal 504 and the optical response 512, depending on the difference between the frequency of
 30 the driving control signal ω_j 506 and the natural frequency 510 of each respective FTL 508. The control signal parameters I_j 505, ω_j 506 and ϕ_j 507 for the control signal $x_j(t)$ 504 for each FTL 508 can be derived knowing the expected optical response output using the well-known function of the (driven) Harmonic Oscillator function: $f(D_j, \omega_j, c_j, \eta_j)$,

where D_j is the amplitude of the optical response output in dioptre. Hence, the design task is reduced to finding an FTL 508 having the parameters c_j 509 and η_j 510, whereby the FTLs natural frequency η_j 510 is not necessarily the frequency ω_j 506, at which it is driven 501, 504 to produce the actual optical response 512, which is the corresponding
 5 Fourier component.

FIG. 5 depicts this scenario by identifying one single branch 500 of the complete lens assembly as shown in Fig. 4. In order to accommodate the mutual phase lags 507 of the optical responses 512, a phase controller 503 is disposed, which “harmonizes” the optical
 10 responses of each FTL by correcting their respective control signal 504 to achieve that all optical responses 512 are in-phase.

In an embodiment, one or more or all FTLs are driven well below their respective natural frequency η_j (resonant frequency), which has the advantage that only a low intensity (the
 15 lowest possible) is required and the phase shift is minimum (approaching zero).

However, the basic idea of having a pure sinusoidal optical response on each FTL may not be desired in practice if there is not a way to optimally construct and assemble the FTLs to fit into a device, especially if the number of lenses is big, e.g., 32 lenses. To
 20 overcome such a problem, there are several alternative embodiments available which will only use few FTLs (2 or 3 FTLs).

FIG. 6 depicts an embodiment of a lens assembly 606 with two FTLs, whereby the first FTL 607 generates an optical response 609 by being driven by a e.g. sinusoidal driving
 25 function 603 or a periodic pulse 603, corresponding to a sum of a limited number of Fourier components of the desired optical response 610. According to the chosen embodiment the limited number of Fourier components may include:

- any one Fourier component;
- 30 • the fundamental component (i.e., the first component of the Fourier series of the where the frequency ω_1 is greater than 0), wherein the frequency ω_1 604 is the inverse of the period of the desired optical response and is consequently named fundamental frequency;

- only odd (1, 3, 5, ...) components;
- only even (2, 4, 6, ...) components;
- less than 10 or less than 5 components.

- 5 The second FTL 608 then compensates for the residual components left by the first FTL by generating an optical response 611 approximating another sum of Fourier components taken from this residual set of components. In order to minimize this residual, the first FTL may be driven with an according control signal 603.
- 10 The controller frequencies ω_1 604 and ω_2 613 correspond to or are near the fundamental or resonance frequency η_1 and η_2 of the first 607 and the second 608 FTL. The frequency ω_1 is the fundamental frequency (inverse of the period) of the desired optical response of the lens assembly, and ω_2 is the main or lowest frequency of the residual Fourier components of the lens assembly's desired optical response. Since the physical properties
- 15 of each of the two FTLs 607 and 608 have to be chosen in a way to provide a satisfactory optical response for a plurality of frequencies corresponding to the Fourier components "assigned" to each of the two FTLs, the difference between frequencies ω_1 and η_1 (if any) and frequencies ω_2 and η_2 (if any) and hence first phase lag ϕ_1 605 and second phase lag ϕ_2 612 might not be the same. Due to this circumstance the signal generators 601 and 615
- 20 driving each of the two FTLs comprise phase controllers 602 and 614, which each compensate for the phase lags ϕ_1 and ϕ_2 between the main (lowest) frequencies ω_1 604 and ω_2 613 of the control signals 603, 616 and the according optical first 609 and second response 611.
- 25 FIG. 7 depicts an embodiment of a lens assembly 706 with three FTLs 707, 708 and 709, whereby a first FTL 707 generates an optical response 710 by being driven by a e.g. sinusoidal driving function 703 or a periodic pulse 703, corresponding to a sum of a limited number of Fourier components of the desired optical response 711. The second FTL 712 in the lens assembly generates an optical response 712 approximating the sum
- 30 of some of the remaining Fourier components in order to compensate for the residual of the first FTL 707, while not necessarily "covering" all remaining Fourier components as is the aim of the embodiment shown in Fig. 6. The third FTL 709 of the lens assembly 706 then generates an optical response 713 approximating the sum of the remaining

Fourier components in order to compensate for the residual of the first 707 and second 708 FTL. Similarly, the Fourier components may include the components described for Fig. 6 in the bullet point section above.

5 Again, it is to be noted that fundamental frequencies ω_1 , ω_2 and ω_3 , referenced in Fig. 7 by numbers 704, 717 and 715, at which the first, the second and third FTL 707, 708 and 709 are driven, correspond to or are near the fundamental or resonance frequencies η_1 , η_2 and η_3 of the first, the second and the third FTL. Consequently, as has been elaborated above for the scenario in Fig. 6, three signal generators 701, 723 and 721 are disposed for
10 each of the three FTLs, whereby each signal controller comprises a respective phase controller 702, 722 and 720. Each phase controller compensates for the respective phase lags ϕ_1 , ϕ_2 and ϕ_3 , referenced in Fig. 7 by numbers 705, 718 and 714, between the respective main (lowest) frequencies ω_1 , ω_2 and ω_3 of the control signals 703, 719 and 716 and the according optical responses 710, 712 and 713.

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The invention also includes a method 800, which is shown in FIG. 8. The method 800 includes a step 801 of controlling an optical power of a lens assembly, which comprises a plurality of focus tunable lenses, FTLs, coaxially disposed along an optical axis of the lens assembly. The method 800 also includes a step 802 of applying to each FTL a
20 respective control signal, thereby generating a periodic optical response of the respective FTL, wherein the optical response of each FTL contributes to the optical power of the lens assembly and is substantially different from the optical response from any other FTL of the plurality of FTLs.

25 In summary, the detailed description and the figures show that an optical system of separately controlled FTLs, which are placed separately and coaxially along an optical axis of an optical system can produce an ideal optical step response or at least a close approximation thereof. Each FTL is thereby driven by signal generator to produce an periodic optical response, which corresponds to a number of Fourier components of the
30 ideal optical step response. The sum of all Fourier components guarantees the generation of a desired ideal optical step response and annihilation of oscillation artifacts and signal delays.

The invention has been described in conjunction with various embodiments as examples as well as implementations. However, other variations can be understood and effected by those persons skilled in the art and practicing the claimed invention, from the studies of the drawings, this disclosure and the independent claims. In the claims as well as in the
5 description the word “comprising” does not exclude other elements or steps and the indefinite article “a” or “an” does not exclude a plurality. A single element or other unit may fulfill the functions of several entities or items recited in the claims. The mere fact that certain measures are recited in the mutual different dependent claims does not
10 indicate that a combination of these measures cannot be used in an advantageous implementation.

CLAIMS

- 1) A focus tunable optical system (400), comprising:
a lens assembly (401) including a plurality of focus tunable lenses, FTLs,
5 coaxially disposed along an optical axis, each FTL contributing to an optical power (301,
302, 303) of the lens assembly, and
a controller configured to control the optical power of the lens assembly by
applying to each FTL a respective control signal (413, 412, 411), thereby generating a
periodic optical response (405, 406, 407) of the respective FTL,
10 wherein the optical response of each FTL is substantially different from the
optical response of any other FTL of the plurality of FTLs.
- 2) The focus tunable optical system according to claim 1, wherein
the optical response of a FTL comprises a natural frequency of the FTL.
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- 3) The focus tunable optical system according to claim 1, wherein
the optical response (512) of a FTL comprises a frequency (506) lower than the
natural frequency (510) of the FTL.
- 20 4) The focus tunable optical system according to claim 1, wherein the controller is
configured to perform a Fourier analysis of a desired optical response (304) and to
generate for each or one or more of the FTLs the respective control signal in proportion
to the sum of one or more Fourier components of the desired optical response.
- 25 5) The focus tunable optical system according to any one of claims 1 to 4, wherein
for each or one or more of the FTLs,
the optical response (609, 611) of the respective FTL (607, 608) comprises one or
more Fourier components of the optical response (610) of the lens assembly.
- 30 6) The focus tunable optical system according to any one of claims 1 to 4, wherein
the optical response of one (607) of the FTLs comprises the lowest Fourier
component of the optical response of the lens assembly.

- 7) The focus tunable optical system according to any one of claims 1 to 4, wherein for each or one or more of the FTLs,
the optical response (609, 611) of the respective FTL (607, 608) comprises only odd Fourier components or only even Fourier components of the optical response of the lens assembly.
- 5
- 8) The focus tunable optical system according to any one of claims 1 to 4, wherein for each or one or more of the FTLs,
the optical response (609, 611) of the respective FTL (607, 608) comprises less than 10, preferably less than 5, Fourier components of the optical response of the lens assembly.
- 10
- 9) The focus tunable optical system according to any one of claims 1 to 4, wherein the plurality of FTLs comprises a first (707), a second (708), and a third (709) FTL,
the optical response (710) of the first FTL approximates a first sum of a number of Fourier components of the desired optical response of the lens assembly,
the optical response (712) of the second FTL approximates a second sum of a subset of the remainder of the Fourier components of the desired optical response of the lens assembly to compensate for a first residual of the first FTL (707),
the optical response (713) of the third FTL approximates a third sum of the remaining Fourier components of the desired optical response of the lens assembly to compensate for a second residual of the second FTL (708), and
the sum (711) of the optical responses of the first, the second and the third FTLs approximates the desired optical response.
- 15
- 20
- 25
- 10) The focus tunable optical system according to any of claims 1 to 9, wherein the optical response of the lens assembly is a periodic staircase function or an approximation of a periodic staircase function.
- 30
- 11) Multifocal display device, comprising:
a focus tunable optical system according to any one of claims 1 to 10.

12) Method for controlling a focus tunable optical system, comprising the steps of:
controlling (801) an optical power of a lens assembly, which comprises a plurality of focus tunable lenses, FTLs, coaxially disposed along an optical axis of the lens assembly; and

5 applying (802) to each FTL a respective control signal, thereby generating a periodic optical response of the respective FTL,

wherein the optical response of each FTL contributes to the optical power of the lens assembly and is substantially different from the optical response from any other FTL of the plurality of FTLs.

10

13) Computer program product comprising a program code for controlling a focus tunable optical system according to any one of claims 1 to 10 or a multifocal display device according to claim 11.

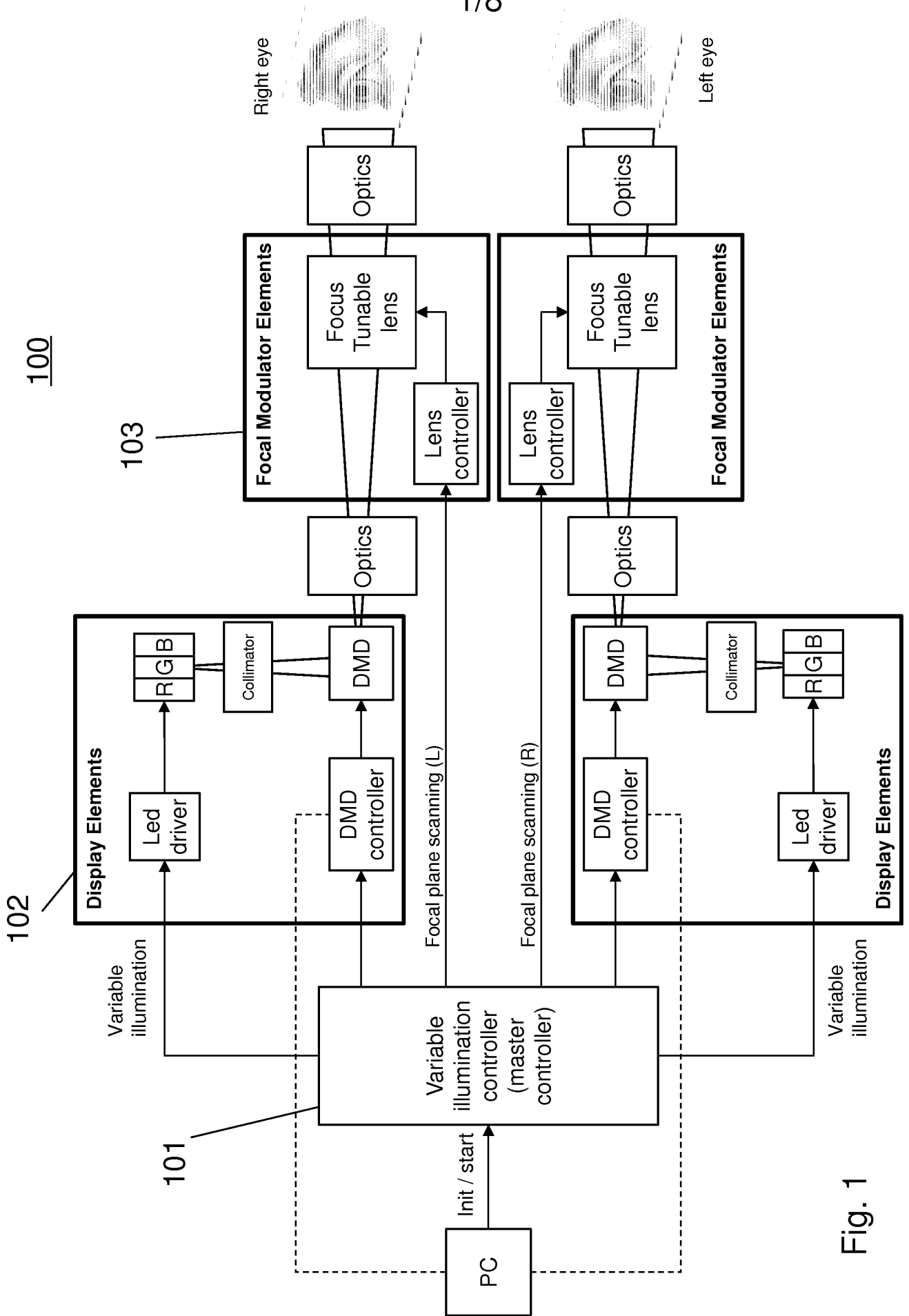


Fig. 1

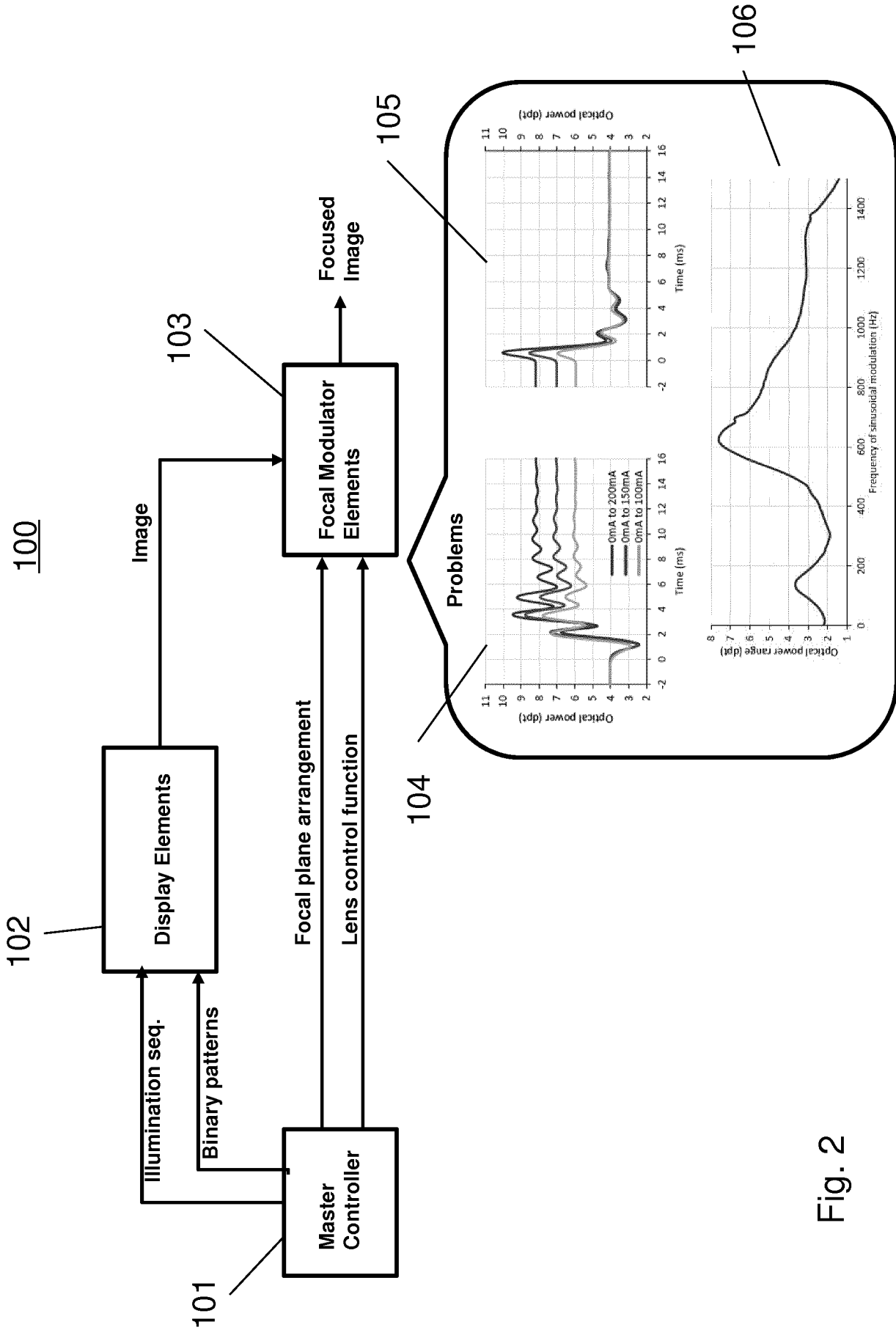


Fig. 2

300

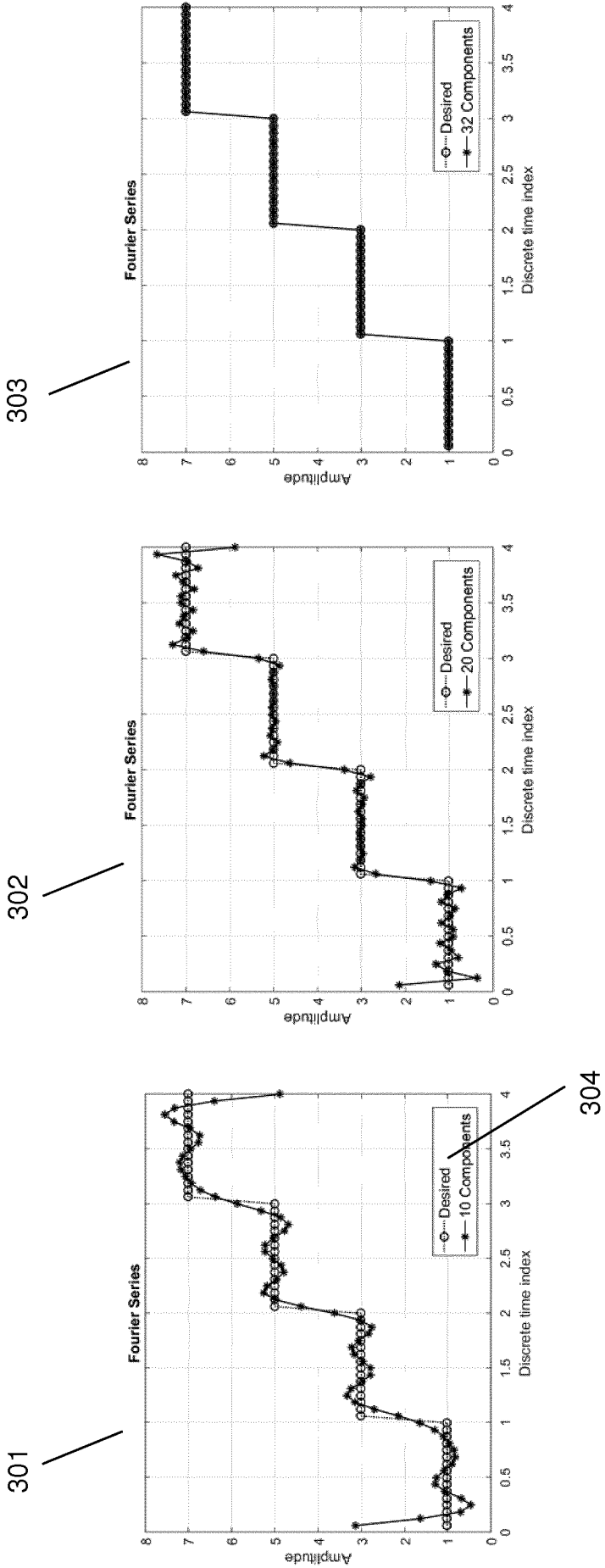


Fig. 3

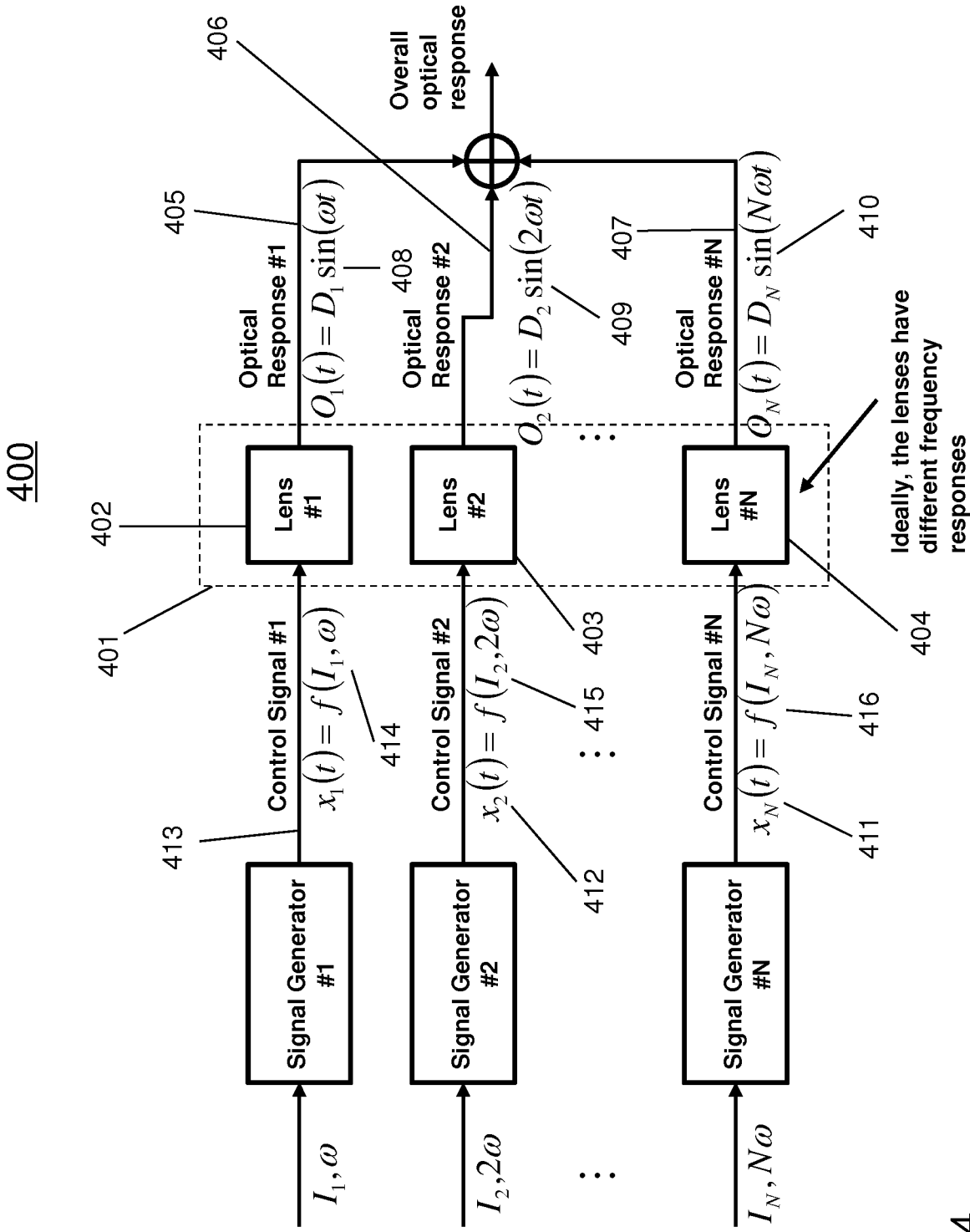


Fig. 4

500

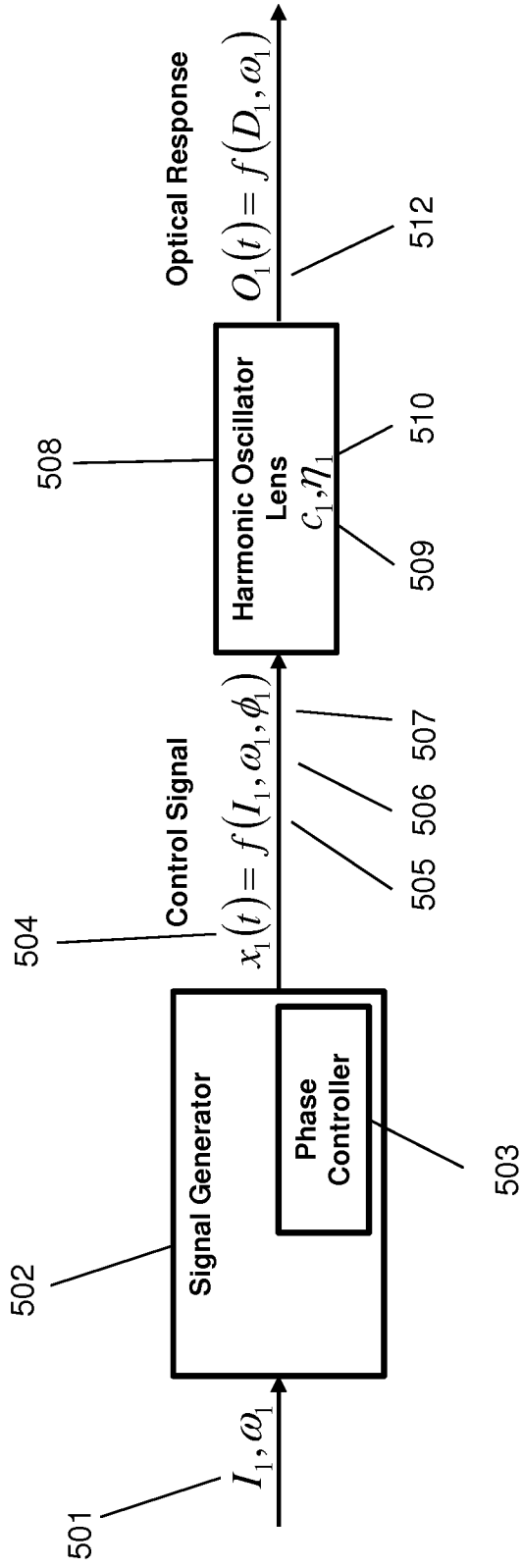


Fig. 5

600

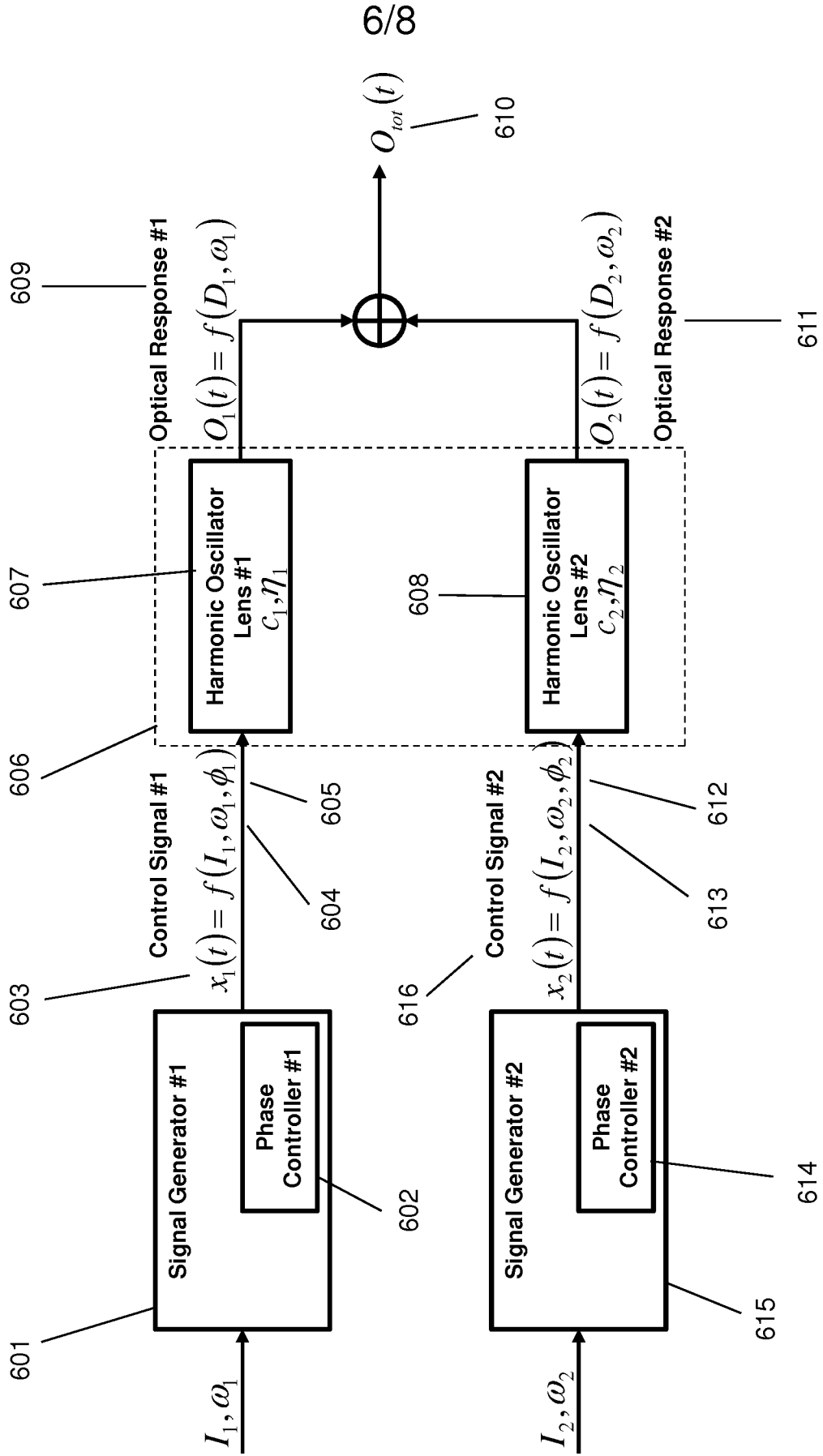


Fig. 6

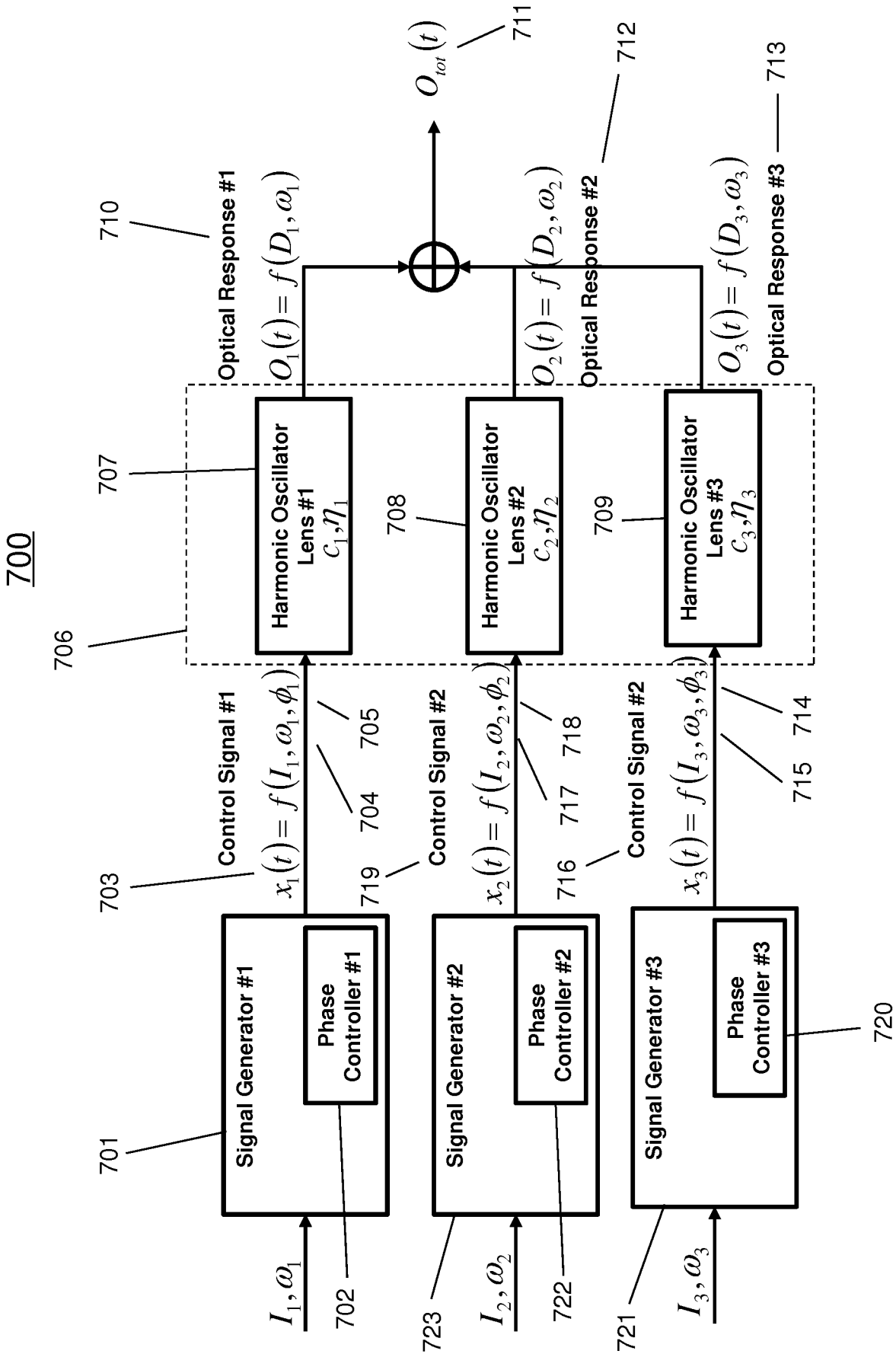


Fig. 7

800

801

Control an optical power of a lens assembly, which comprises a plurality of focus tunable lenses, FTLs, coaxially disposed along an optical axis of the lens assembly.

802

Apply to each FTL a respective control signal, thereby generating a periodic optical response of the respective FTL, wherein the optical response of each FTL contributes to the optical power of the lens assembly and is substantially different from the optical response from any other FTL of the plurality of FTLs.

Fig. 8

INTERNATIONAL SEARCH REPORT

International application No PCT/EP2017/075657
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A. CLASSIFICATION OF SUBJECT MATTER INV. G02B27/01 G02B3/14 H04N13/395 ADD.				
According to International Patent Classification (IPC) or to both national classification and IPC				
B. FIELDS SEARCHED				
Minimum documentation searched (classification system followed by classification symbols) G02B H04N				
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched				
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data				
C. DOCUMENTS CONSIDERED TO BE RELEVANT				
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.		
X A A	W0 02/33657 A2 (BATCHKO ROBERT [US]) 25 April 2002 (2002-04-25) figure 3 page 21; table III ----- Optotune: "Fast Electrically Tunable Lens EL-10-30 Series", Datasheet: EL-10-30-Series, 4 April 2016 (2016-04-04), XP055484804, Retrieved from the Internet: URL:https://www.stemmer-imaging.de/media/u ploads/optics/10/102966-Optotune-EL-10-30. pdf [retrieved on 2018-06-15] cited in the application figures 12, 13, 14 ----- -/--	1,3,5,6, 8,10-13 2,4,7,9 1-13		
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.				
* Special categories of cited documents : <table style="width: 100%; border: none;"> <tr> <td style="width: 50%; border: none; vertical-align: top;"> "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed </td> <td style="width: 50%; border: none; vertical-align: top;"> "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family </td> </tr> </table>			"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family
"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family			
Date of the actual completion of the international search 15 June 2018	Date of mailing of the international search report 02/07/2018			
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Serbin, Jesper			

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International application No
PCT/EP2017/075657

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 2004/114203 A1 (BATCHKO ROBERT G [US]) 17 June 2004 (2004-06-17) figure 1 -----	1-13
A	EP 3 226 558 A1 (DAVALOR SALUD S L [ES]) 4 October 2017 (2017-10-04) figures 1, 2 -----	1-13
A	US 2006/232498 A1 (SEO CHEONG S [KR] ET AL) 19 October 2006 (2006-10-19) paragraph [0014] figures 3, 4 -----	1-13
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