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(54) **METHOD FOR CALIBRATING A MEMS DEVICE**

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(58) **Field of Search** 385/18-19, 16-24, 385/52; 356/140-141.5; 398/12, 19, 16

(56) **References Cited**

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6,411,751 B1 * 6/2002 Giles et al. 385/16

* cited by examiner

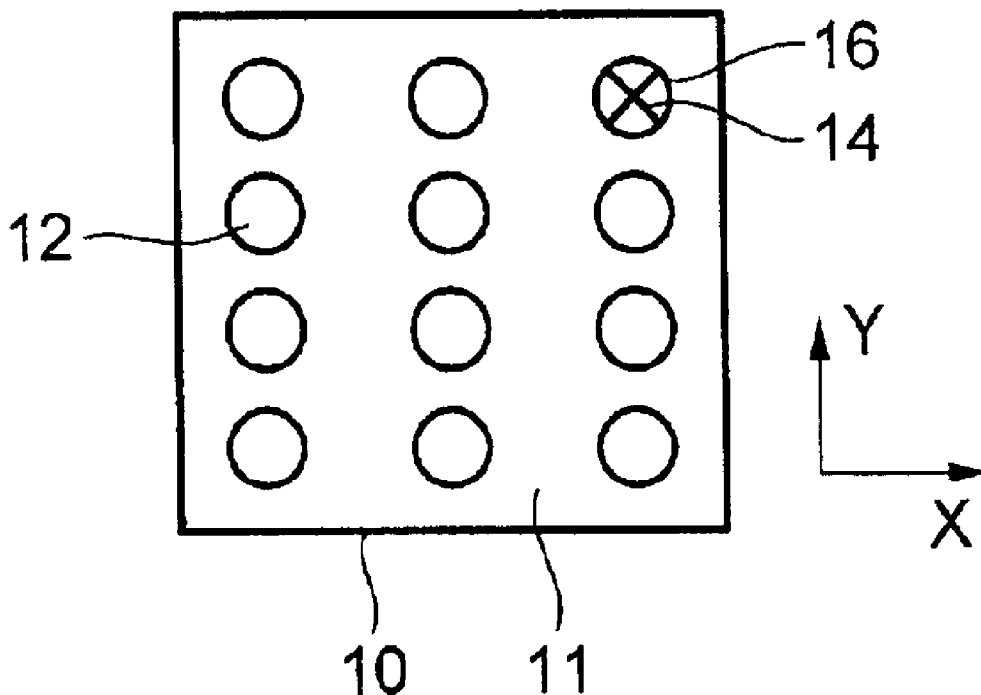
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(57) **ABSTRACT**

A method of calibrating a crossconnect including a MEMS device and another optical device, each of which further include a plurality of elements, the method including determining a relationship between an applied voltage and an angle response for a number of the elements of the MEMS device, determining a function of beam position and element position for the number of the elements of the MEMS device, assembling the MEMS device and the another optical device to produce the crossconnect, applying voltages to make sample connections between the MEMS device and the another optical device based on the relationship and the function, determining a transformation for the sample connections caused by packaging the crossconnect, and re-determining the relationship and the function based on the transformation. The method may be iterated more than once to achieve a more accurate determination.

21 Claims, 7 Drawing Sheets



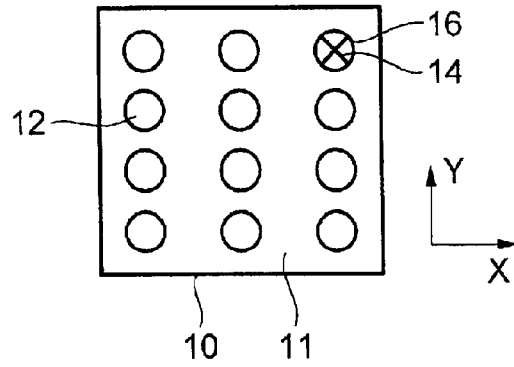


FIG. 1

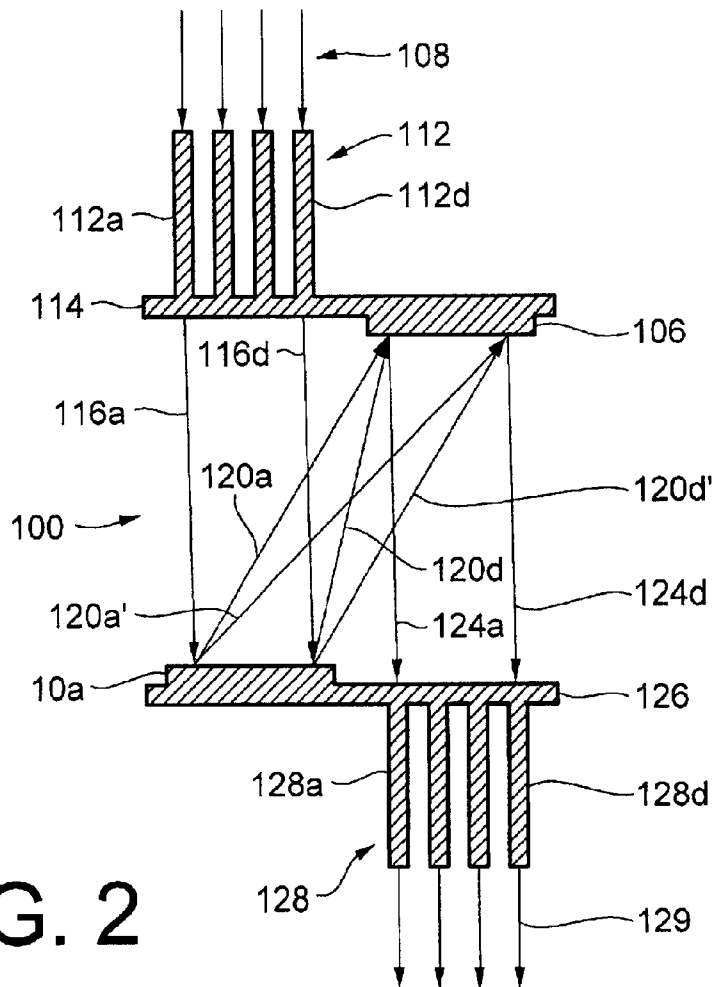


FIG. 2

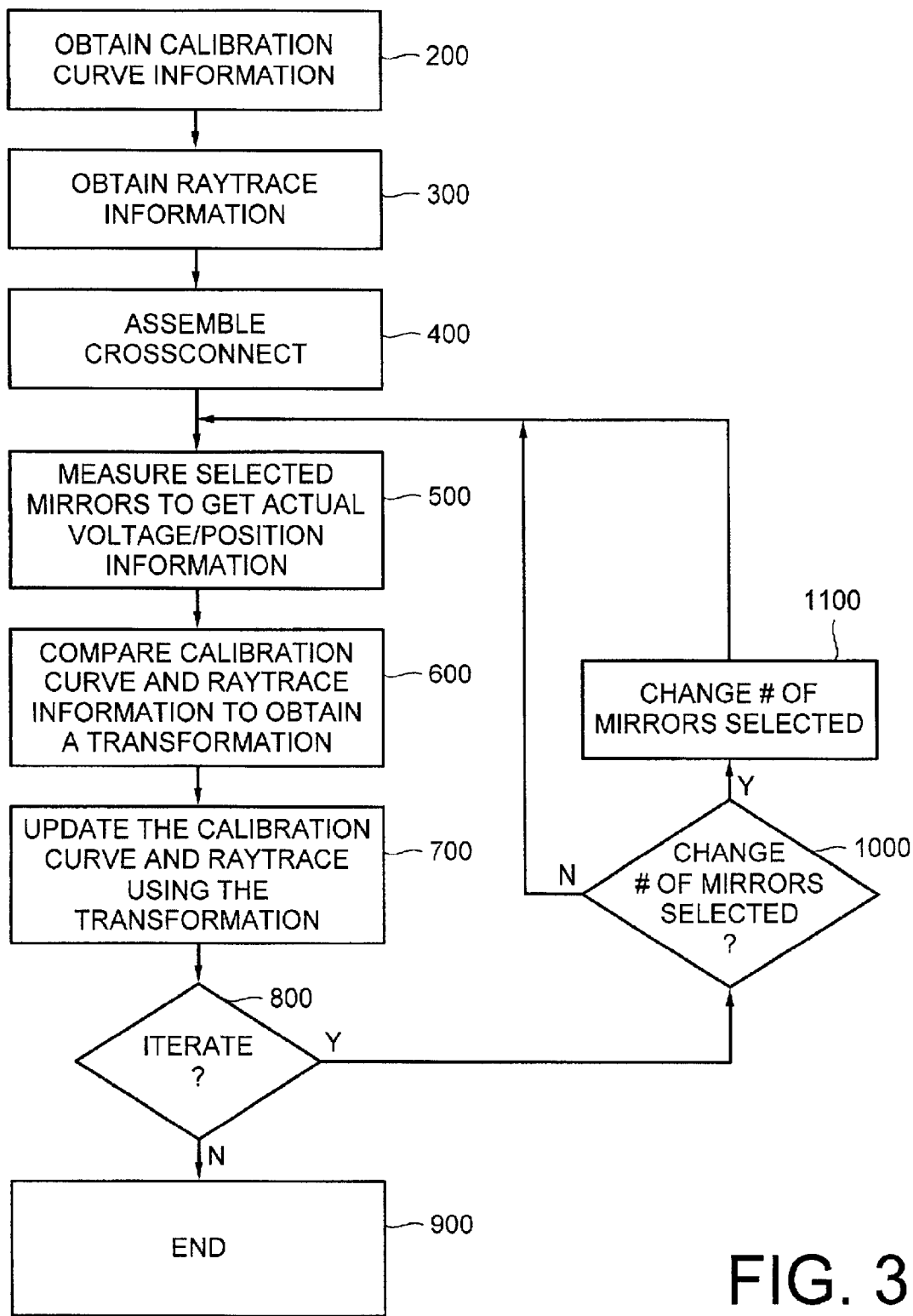


FIG. 3

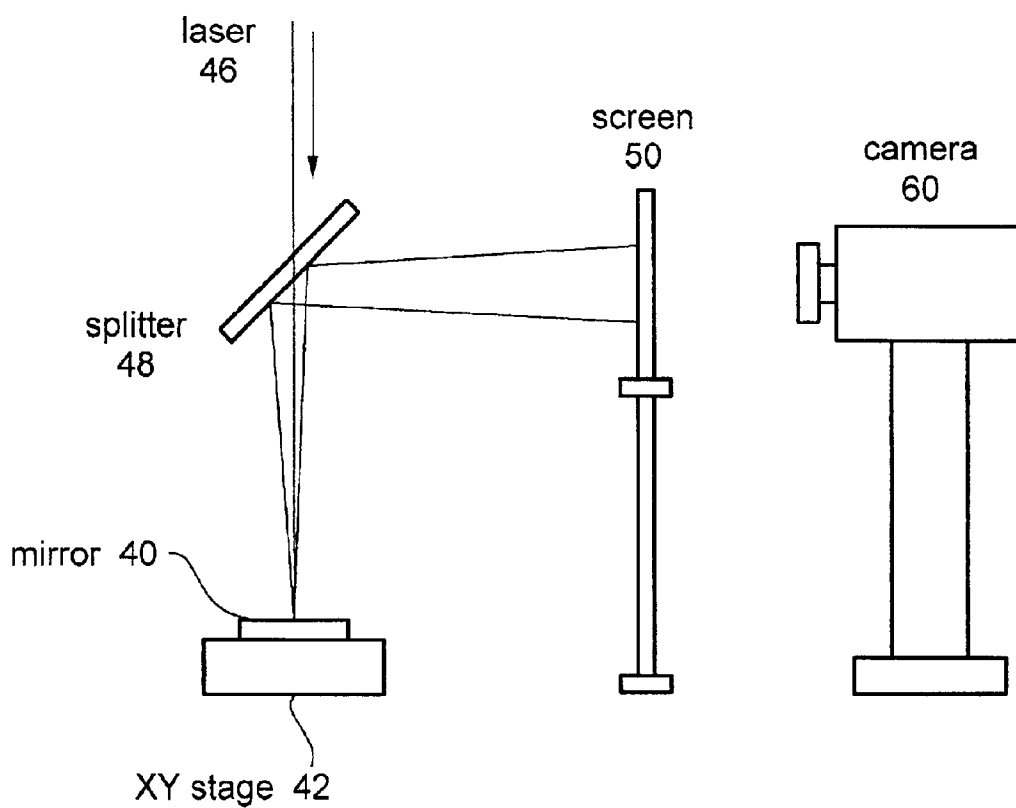


FIG. 4

72 {
72 {

0101	0102	0103	0104	0105	0106	0107	0108	0109	0110	0111	0112	0113	0114	0115	0116	0117	0118	0119	0120	0121	0122	0123	0124	0125	0126	0127	0128	0129	0130	0131	0132	0133	0134	0135	0136	0137	0138	0139	0140	0141	0142	0143	0144	0145	0146	0147	0148	0149	0150	0151	0152	0153	0154	0155	0156	0157	0158	0159	0160	0161	0162	0163	0164	0165	0166	0167	0168	0169	0170	0171	0172	0173	0174	0175	0176	0177	0178	0179	0180	0181	0182	0183	0184	0185	0186	0187	0188	0189	0190	0191	0192	0193	0194	0195	0196	0197	0198	0199	0200
0201	0202	0203	0204	0205	0206	0207	0208	0209	0210	0211	0212	0213	0214	0215	0216	0217	0218	0219	0220	0221	0222	0223	0224	0225	0226	0227	0228	0229	0230	0231	0232	0233	0234	0235	0236	0237	0238	0239	0240	0241	0242	0243	0244	0245	0246	0247	0248	0249	0250	0251	0252	0253	0254	0255	0256	0257	0258	0259	0260	0261	0262	0263	0264	0265	0266	0267	0268	0269	0270	0271	0272	0273	0274	0275	0276	0277	0278	0279	0280	0281	0282	0283	0284	0285	0286	0287	0288	0289	0290	0291	0292	0293	0294	0295	0296	0297	0298	0299	0300
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0701	0702	0703	0704	0705	0706	0707	0708	0709	0710	0711	0712	0713	0714	0715	0716	0717	0718	0719	0720	0721	0722	0723	0724	0725	0726	0727	0728	0729	0730	0731	0732	0733	0734	0735	0736	0737	0738	0739	0740	0741	0742	0743	0744	0745	0746	0747	0748	0749	0750	0751	0752	0753	0754	0755	0756	0757	0758	0759	0760	0761	0762	0763	0764	0765	0766	0767	0768	0769	0770	0771	0772	0773	0774	0775	0776	0777	0778	0779	0780	0781	0782	0783	0784	0785	0786	0787	0788	0789	0790	0791	0792	0793	0794	0795	0796	0797	0798	0799	0800
0801	0802	0803	0804	0805	0806	0807	0808	0809	0810	0811	0812	0813	0814	0815	0816	0817	0818	0819	0820	0821	0822	0823	0824	0825	0826	0827	0828	0829	0830	0831	0832	0833	0834	0835	0836	0837	0838	0839	0840	0841	0842	0843	0844	0845	0846	0847	0848	0849	0850	0851	0852	0853	0854	0855	0856	0857	0858	0859	0860	0861	0862	0863	0864	0865	0866	0867	0868	0869	0870	0871	0872	0873	0874	0875	0876	0877	0878	0879	0880	0881	0882	0883	0884	0885	0886	0887	0888	0889	0890	0891	0892	0893	0894	0895	0896	0897	0898	0899	0900
0901	0902	0903	0904	0905	0906	0907	0908	0909	0910	0911	0912	0913	0914	0915	0916	0917	0918	0919	0920	0921	0922	0923	0924	0925	0926	0927	0928	0929	0930	0931	0932	0933	0934	0935	0936	0937	0938	0939	0940	0941	0942	0943	0944	0945	0946	0947	0948	0949	0950	0951	0952	0953	0954	0955	0956	0957	0958	0959	0960	0961	0962	0963	0964	0965	0966	0967	0968	0969	0970	0971	0972	0973	0974	0975	0976	0977	0978	0979	0980	0981	0982	0983	0984	0985	0986	0987	0988	0989	0990	0991	0992	0993	0994	0995	0996	0997	0998	0999	1000

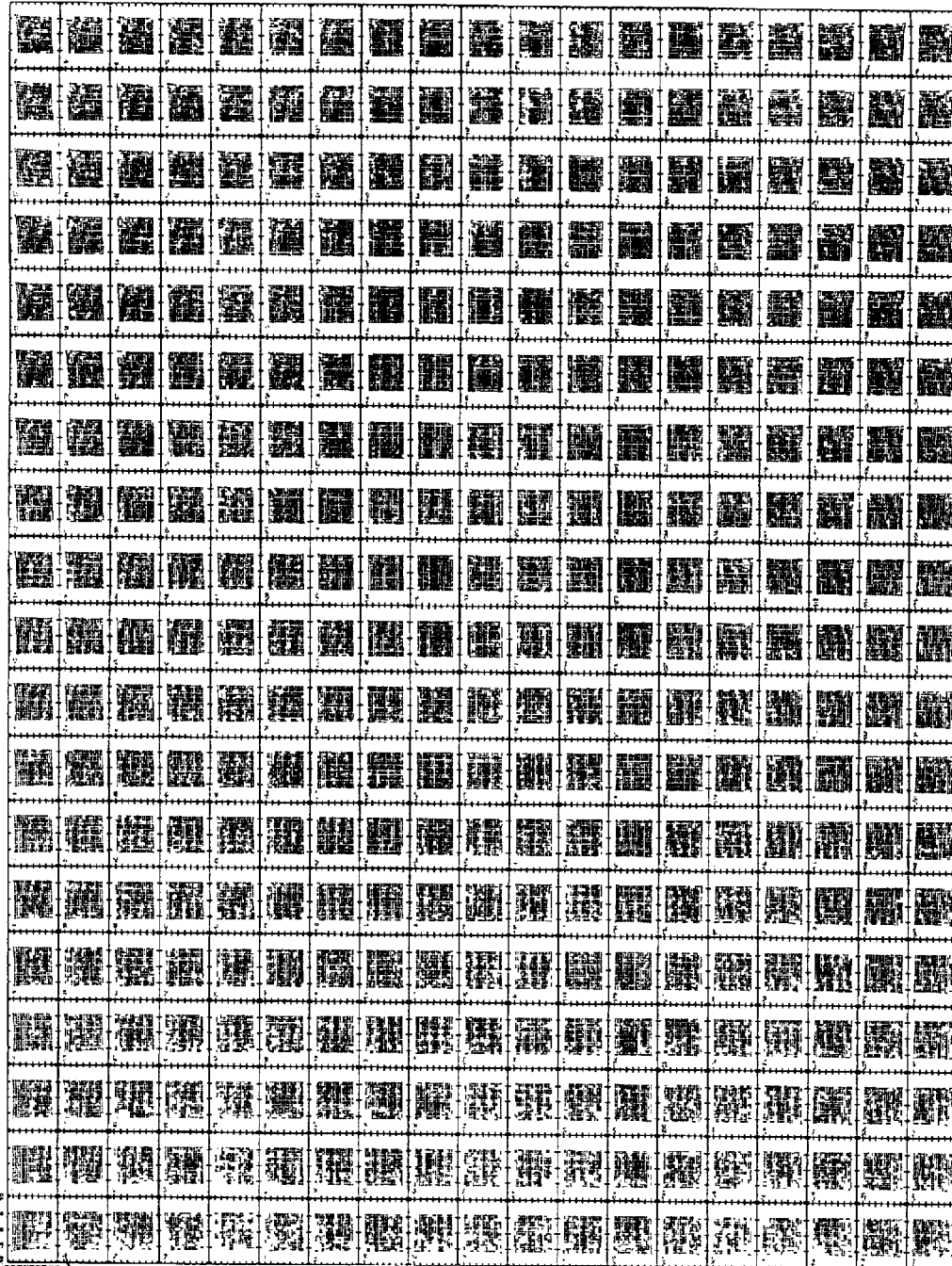
70 {

74 {

FIG. 5

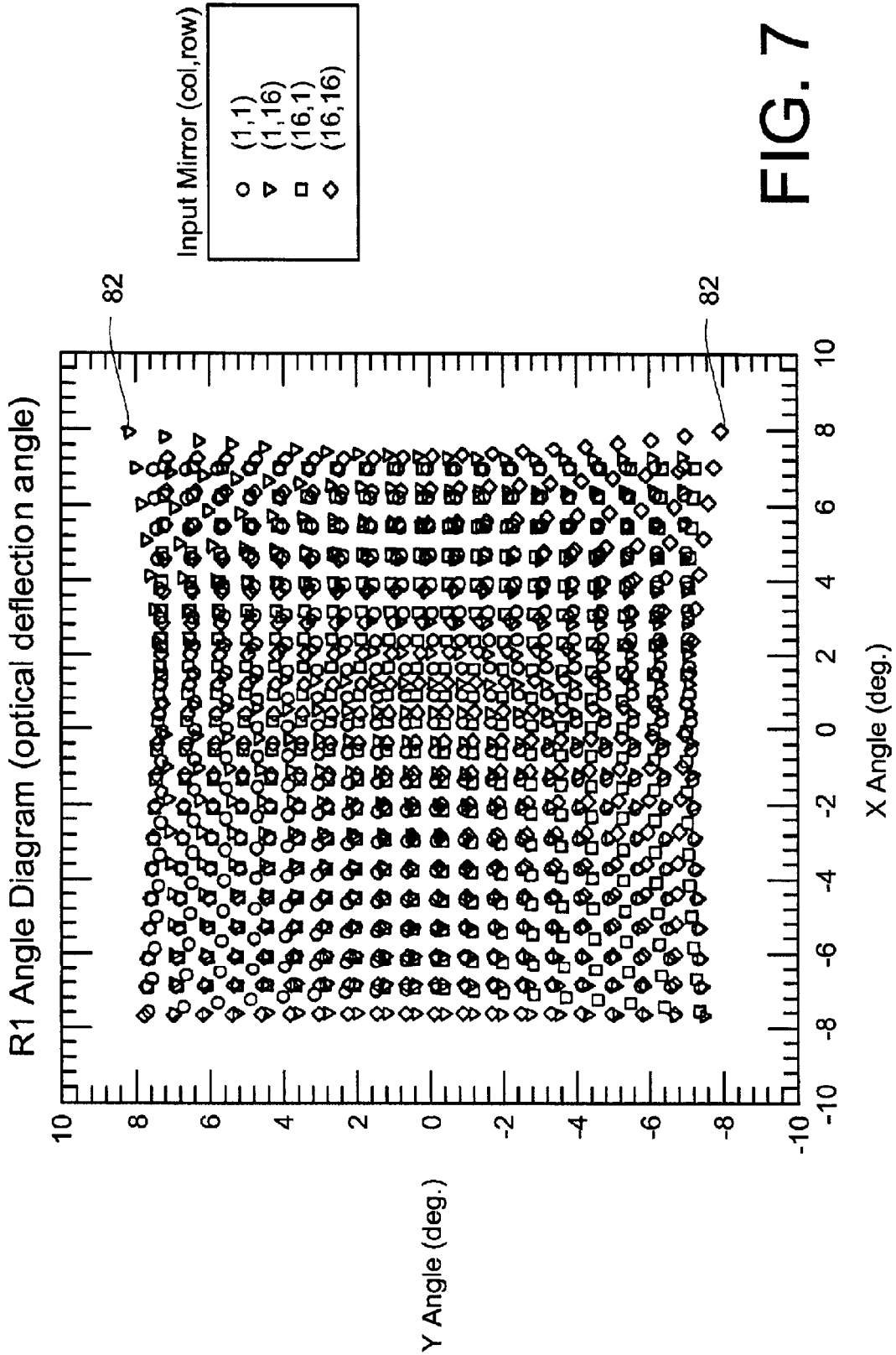
(10X) bad mirrors = 0 (1 elect) / 2 (2 elect) / 4 (3 elect) / 0 (4 elect) Version HV 1.0 / Sun Jun 14 20:44:02 2001 package dot

Spot Diagram for R1 3/6/01 1:19:39 PM



80 {
82

FIG. 6



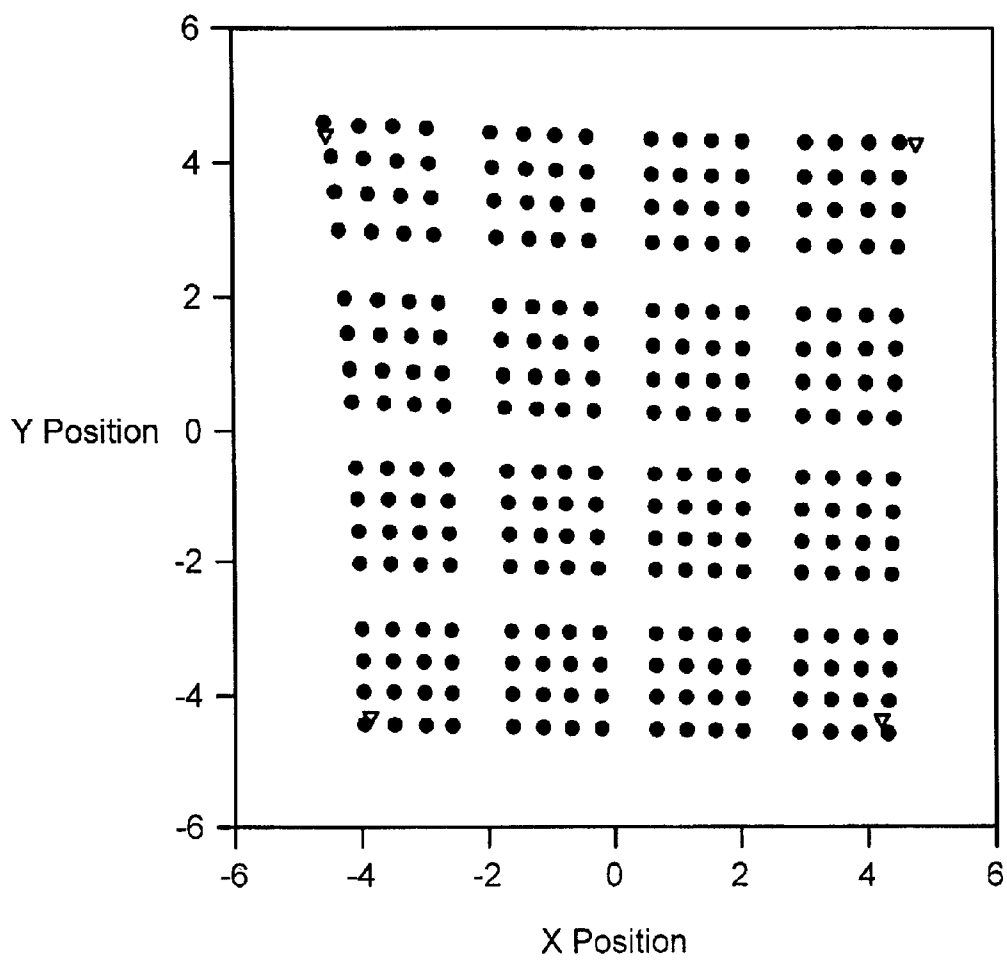


FIG. 8

METHOD FOR CALIBRATING A MEMS DEVICE

TECHNICAL FIELD

The present invention relates to the field of fiber optic communications and in particular, to a method for calibrating a micro-electromechanical (MEMS) device.

BACKGROUND ART

In fiber optic communication systems, signal routing is the ability to direct a signal received from one of a plurality of input fibers or ports to any of a plurality of output fibers or ports without regard to the frequency and polarization of the optical signal. Signal routing is essential for directing an optical signal carrying data to an intended location.

Free-space optical crossconnects allow interconnecting among input and output ports in a reconfigurable switch fabric. An example of such an optical crossconnect utilizes an array of MEMS tilting mirror devices as the fabric. By adjusting the tilt angles of the MEMS mirror devices, optical signals can be directed to various destinations, i.e., to numerous output fibers.

Arrays of two-axis tilt mirrors implemented using micro-electromechanical systems (MEMS) technology allow for the construction of large scale optical crossconnects for use in optical systems. Optical crossconnects are commonly employed to connect a number of input optical paths to a number of output optical paths. A typical requirement of optical crossconnects is that any input be capable of being connected to any output. One example of a MEMS device is the MEMS mirror array **10** depicted in FIG. 1. The mirror array **10** includes a plurality of tilt mirrors **12** formed on a substrate **11**, mounted to springs **14** and controlled by electrodes (not shown). Each mirror **12** is approximately 100–500 microns across, may be shaped as square circular or elliptical, and is gimbaled with the tilt angle being selectively determined by the amount of voltage applied to the control electrodes. Gimbaled mirrors are capable of operatively rotating or tilting about at least two axes, for example, orthogonal X-Y axes of rotation. With two axes, one axis is termed the mirror axis, the other axis (typically orthogonal to the mirror axis) is the gimbaled axis. Gimbaled mirror configurations are described in U.S. Pat. No. 6,201,631 to Greywall. Other mirrors, with only one axis, are also known in the art.

Further details of the operation of the MEMS mirror array **10** are found in copending U.S. patent application Ser. No. 09/415,178, filed Oct. 8, 1999. Utilizing two or more such tilt mirror arrays **10** to form an optical crossconnect is disclosed in copending U.S. patent application Ser. No. 09/410,586 filed Oct. 1, 1999. Techniques associated with monitoring mirror position are disclosed in copending U.S. patent application Ser. No. 09/414,621 filed Oct. 8, 1999. Techniques for detecting mirror position are disclosed in copending U.S. patent application Ser. No. 09/518,070 filed Mar. 3, 2000. The entire contents of each of the above-mentioned patent applications are hereby incorporated by reference.

The use of one or more MEMS tilt mirror arrays in conjunction with a lens array is disclosed in co-pending U.S. patent application Ser. No. 09/512,174, filed Feb. 24, 2000, the entire content of which is also incorporated herein by reference. As disclosed in that application, various optical crossconnect configurations of compact size (i.e. minimal spacing between crossconnect components) and exhibiting

minimal optical power loss can be realized. One such optical crossconnect **100** discussed in the aforementioned application is depicted in FIG. 2. Crossconnect **100** receives input optic signals **108** through a plurality of optic fibers **112a**, **112b**, **112c**, **112d**, preferably formed in an array **112** as is well known in the art. For ease of illustration, fiber array **112** is shown as a one-dimensional array having four fibers **112a**, **112b**, **112c**, **112d**. It is in any event to be understood that fiber array **112**, as well as other fiber arrays discussed herein are preferably two-dimensional arrays such as, for example, N×N arrays.

Fiber array **112** transmits the optical signals **108** to an array of lenses **114** that function as collimating lenses. The lens array **114** is positioned relative to fiber array **112** so that each lens communicates with a corresponding fiber for producing beams **116** from the optic signals **118**. Thus, beam **116a** is produced from a signal carried by fiber **112a**, beam **116b** is produced from a signal carried by fiber **112b**, etc.

A first MEMS tilt mirror array **10a**, also referred to as the input array, is positioned in alignment with the lens array **114** so that each mirror element **12a** will receive a corresponding beam **116**. The mirror elements **12a** are operatively tilted, in a manner discussed in application Ser. No. 09/415,178, to reflect the respective beams **116** to a second or output MEMS mirror array **10b** positioned in optical communication with MEMS array **10a**. Depending on the tilt angle of each mirror element **12a** in input MEMS array **10a**, the reflected signals can be selectively directed to specific mirror elements **12b** in output MEMS array **10b**.

To illustrate this principle, beam **116a** is shown in FIG. 2 generating reflection beams **120a** and **120a'** and beam **116d** is shown generating reflection beams **120d** and **120d'**. The particular trajectory of the reflection beams is determined by the tilt angle of the mirrors in the MEMS array **10a**, on which the beam **116** is incident. These beams are received by mirror elements **12b** in the output MEMS array **10b** and are directed as beams **124a** to an output lens array **126**. An output fiber array **128** is aligned with lens array **126** to receive and transmit output optical signals **129**. Thus, lens array **126** couples beams **124** into the output fiber array **128**.

MEMS devices **10a** and **10b**, and in particular, tilting mirror devices **12a** and **12b**, are fairly sensitive devices which may be moved by the application of a force and may require fairly precise positioning. Knowledge of the devices' **10a** and **10b** response to an applied force is important to controlling the position of the mirrors **12a** and **12b**. Further, acquiring this knowledge as quickly as possible is also an important criterion.

SUMMARY OF THE INVENTION

The present invention is directed to a method of calibrating a MEMS device such that the response of each of the elements of the MEMS device to the applied force is known.

The present invention is directed to a method of calibrating a MEMS device such that the MEMS device is calibrated quickly and accurately.

In the present invention, various voltages are applied via electrodes to create potentials between mirrors of the MEMS device and the electrodes to move the mirrors. The potentials cause the mirrors to rotate. The relationship between the applied voltage and the mirror rotation (in angle or position) is recorded as a calibration curve. In one embodiment, this relationship is determined for every mirror in the MEMS device. Next, the trajectory of a beam reflected by a mirror is determined as a function of mirror position. Determining the trajectory of the beam determines where the beam is

directed by the mirror. In an optical cross-connect the beam is directed to a location on another component (e.g. another moving mirror in a different array, a non-moving optical element, an output fiber, etc.) In one embodiment, raytracing is used to determine where a beam will be directed as a function of mirror position. The angles of the mirrors associated with directing the beam to a particular location are determined from the ray tracing. In one embodiment, this relationship is determined for every mirror in the MEMS device. The calibration curve and the raytraces provide the voltages to be applied to move mirrors in a perfectly aligned cross-connect to direct a beam to desired locations.

Once this information is obtained, the optical interconnect is actually physically assembled. A subset of the mirrors are tested to determine the voltages that are actually needed to move the mirrors to direct the beams to the desired locations. The differences between the voltages actually required to make the connection (possibly after some minor adjustments) and the voltages provided based upon the calibration curve and the raytraces are determined. These differences represent a transformation that indicates the differences between a perfectly aligned crossconnect and a crossconnect as actually physically assembled.

The transformation may be more complicated than just a scalar, numerical value or values. The transformation may be a mathematical transformation, which relates the actual experimental voltages to calculated voltages of the perfectly aligned crossconnect, and may include a set of multivariable polynomials that describe the rotation, translation, tilt and distortion. With regard to the offset, once an initial and partial set of voltages are determined, the coefficients of the polynomial mapping are calculated and applied to calculate a new set of voltages. The transformation is used to update the values represented by the calibration curve and the raytraces. New actual measurements may then be taken and compared to the updated values represented by the calibration curve and the raytraces. The updated values and the actual measured values begin to converge, after, in a preferred embodiment, two to three times. In a preferred embodiment, a different number of mirrors are actually measured in each iteration. In a more preferred embodiment, more mirrors are actually measured in each subsequent iteration (each mirror being closer to actual in subsequent iterations). In a more preferred embodiment, four mirrors are used for the first iteration and 16 for a second.

One advantage of the method of the present invention is that every mirror need not be tested or trained after the crossconnect is assembled, thereby decreasing the time needed to calibrate the crossconnect.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a conventional MEMS mirror array.

FIG. 2 illustrates a conventional optical crossconnect.

FIG. 3 illustrates a flowchart in one exemplary embodiment of the present invention.

FIG. 4 illustrates an arrangement for collecting the voltage versus position or voltage versus angle information, in one exemplary embodiment of the present invention.

FIG. 5 illustrates angle vs. voltage data for a MEMS device 10 with 16x16 array of gimbale mirrors, in one exemplary embodiment of the present invention.

FIG. 6 illustrates the results of raytracing, in one exemplary embodiment of the present invention.

FIG. 7 illustrates the a portion of the results of FIG. 6 at better resolution.

FIG. 8 illustrates calculated position coordinates for an input mirror to hit all output mirrors for a given crossconnect, in one exemplary embodiment of the present invention.

DETAILED DESCRIPTION

The present invention is directed to a method of calibrating a MEMS device 10 such that the response of each of the elements 12 of the MEMS device 10 to the applied force is known. The present invention is described below in the context of a gimbale configuration, but is also applicable to a one axis configuration.

FIG. 3 illustrates a flowchart in one exemplary embodiment of the present invention. Various voltages are applied via electrodes to create potentials between mirrors of the MEMS device and the electrodes to move the mirrors. The potentials cause the mirrors to rotate. The relationship between the applied voltage and the mirror rotation (in angle or position) is recorded as a calibration curve. Obtaining the calibration curve is step 200 of FIG. 3. In one embodiment, this relationship is determined for every mirror in the MEMS device. Next, the trajectory of a beam reflected by the beam to another location (i.e. another moving mirror in a different array, a non-moving optical element, an output fiber, etc.) is determined as a function of mirror position. In one embodiment, raytracing is used to determine where a beam will be directed as a function of mirror position. The angles of the mirrors associated with directing the beam to a particular location are determined from the raytracing. Obtaining the calibration curve is step 300 of FIG. 3. In one embodiment, this relationship is determined for every mirror in the MEMS device. The calibration curve and the raytraces provide the voltages to be applied to move mirrors in a perfectly aligned cross-connect to direct a beam to desired locations.

Once this information is obtained, the optical interconnect is actually physically assembled in step 400 of FIG. 3. A subset of the mirrors are tested to determine the voltages that are actually needed to move the mirrors to direct the beams to the desired locations in step 500 of FIG. 3. The differences between the voltages actually required to make the connection (possibly after some minor adjustments) and the voltages provided based upon the calibration curve and the raytraces are determined in step 600 of FIG. 3. These differences represent a transformation that indicates the differences between a perfectly aligned crossconnect and a crossconnect as actually physically assembled.

The transformation may be more complicated than just a scalar, numerical value or values. The transformation may be a mathematical transformation, which relates the actual experimental voltages to calculated voltages of the perfectly aligned crossconnect, and may include a set of multivariable polynomials that describe the rotation, translation, tilt and distortion. With regard to the offset, once an initial and partial set of voltages are determined, the coefficients of the polynomial mapping are calculated and applied to calculate a new set of voltages. The transformation is used to update the values represented by the calibration curve and the raytraces in step 700 of FIG. 3.

The process may then be iterated in step 800 or not in step 900. In steps 1000 and 1100 of FIG. 3, a different number of mirrors may be selected.

New actual measurements may then be taken and compared to the updated values represented by the calibration curve and the raytraces. The updated values and the actual measured values begin to converge, after, in a preferred

embodiment, two to three times. In a preferred embodiment, a different number of mirrors are actually measured in each iteration. In a more preferred embodiment, more mirrors are actually measured in each subsequent iteration (each mirror being closer to actual in subsequent iterations). In a more preferred embodiment, four mirrors are used for the first iteration and 16 for a second.

More specifically, prior to assembly in an optical interconnect, the MEMS device **10** is tested to determine the relationship between the applied voltage and the angle response. As discussed above, in one embodiment, the elements **12** of the MEMS device **10** are mirrors, which are moved by electrostatic force between the mirrors and a proximate electrode. When a voltage is applied to the electrode, a potential difference between the mirror and the electrode is created, which causes the mirror to rotate in both an X and Y angle direction. Various, exemplary voltages are applied to the mirrors to record their angle direction rotation. Measurements are taken for various mirrors at various applied voltages and the rotation in the X and Y angle direction as well as the resulting beam position may be recorded.

FIG. 4 illustrates an arrangement for collecting the voltage versus position or voltage versus angle information. A mirror **40** is placed on an X-Y stage **42** and X and Y voltages are applied. The mirror **40** moves and directs a beam from laser **46** to a screen **50** via splitter **48**. The position of the beam on the screen **50** is measured by a camera **60**. These measurements are taken for various voltages for various mirrors.

As described above, a finite set of data is measured. This finite set of data is fit to a mathematical function and the results are the coefficients of the mathematical function that describe the voltage versus angle (or voltage versus position) relationship for each MEMS mirror for an inclusive range of voltages. In a preferred embodiment, the mathematical functions is a polynomial. Process variations present during the manufacture of each mirror of the array may lead to different mirror properties and each individual mirror should be characterized at as many voltages as possible to obtain more accurate information. Mirrors that are not functional, either because of bad electrodes or other reasons, are marked and filtered out of the database.

For input and output arrays with a large number of mirrors, all input mirrors may not be able to access all output mirrors. Further, even if accessible, variations in electrode performance may be such that the array should be divided into smaller sections or subunits of mirrors for control purposes. In one preferred embodiment, a mirror array is divided in quadrants for control purposes.

FIG. 5 illustrates angle vs. voltage data for an exemplary MEMS device **10** with 16x16 array of gimbaled mirrors. Each square **70** is a response (angle as a function of voltage) of each mirror. Scanning is performed to determine bad mirrors. The cross-hatching indicates a bad mirror **72** (there are seven bad mirrors **72** in FIG. 5). Scanning may be performed by applying a fixed voltage, from a lower limit (for example, 0 V) to an upper limit (for example, 160 V), in fixed increments (for example, 20 V).

The array of dots **74** in FIG. 5 indicates the response of the gimbaled mirror. As described above, the objective is to obtain a relationship between the voltages applied to the mirrors and the gimbal and the tilt of the mirrors along the two axes. It should be noted that the present invention is not limited to a gimbaled mirror configuration and is further applicable to modulator or a dynamic equalizer applications.

The measured data is fit to a mathematical function (in one example, a polynomial) to estimate how each mirror will react and where the beam will be positioned for voltages not actually measured. Due to the asymmetry of electrodes (and other phenomena), a single mathematical function or polynomial for all data may not be appropriate. In one exemplary embodiment, a different mathematical function or polynomial is used for each quadrant of the mirror array. The result(s) of the mathematical function or polynomial fit is a calibration curve.

Once the calibration curve is obtained as described above, the next step is to determine the angle of a mirror necessary to direct a beam from the mirror (such as mirror **12a** in FIG. 2) in a first array (such as MEMS devices **10a** in FIG. 2) to a location (such as mirror **12b**) in a second array (such as MEMS devices **10b**). The location need not be mirror in a second array, but rather could be an output array of non-moving fibers or other location. The determination of how to direct a signal from a mirror in a first array to the location (a mirror in a second array) may be a simple geometric calculation, using the position of the mirror and the desired location of the beam. This may be accomplished by raytracing.

FIG. 6 illustrates exemplary results from a geometric model in a perfect environment with perfect alignment. Each square **80** represents a mirror **12a** in MEMS devices **10a**. The X axis is the angle of the mirror **12a** on the first axis and the Y axis is the angle of the mirror **12a** on the second axis. Each dot **82** represents the location of the beam at a location (for example, on the second array) as a function of the angle (or position) of the mirror in the MEMS device **10a**. Conventional raytracing software called OSLO is available from Lambda Research Corp. of Littleton, Mass.

At the resolution illustrated FIG. 6, all the dark squares **80** look somewhat similar. However, FIG. 7 illustrates the overlay of position data for four exemplary mirrors (1,1), (1,16), (16,1), and (16,16) from FIG. 6 at better resolution. As can be seen, the four mirror responses are not the same.

After the step of raytracing, the crossconnect **100** is assembled.

The next step is to make sample actual connections from sample mirrors in MEMS devices **10a** to sample mirrors in MEMS devices **10b** by applying the voltage indicated by the calibration curve at the angle indicated by the raytracing. Best results are obtained when corner mirror to corner mirrors are used as samples because these connections are the most demanding connections from a tilt angle perspective.

The next step is determining the transformation caused by assembling the crossconnect **100**. This entails determining whether each of the expected connections was actually made and the strength of the received signal for each connection. It is likely that not all connections will be made and those that are made do not have the best signal strength. If the signal strength is not satisfactory, a transformation is determined to improve the signal strength.

The transformation may be more complicated than just scalar, numerical values. The transformation may relate the actual experimental voltages to calculated voltages of a perfectly aligned crossconnect, and may include a set of multivariable polynomials that describe the rotation, translation, tilt and distortion. With regard to the transformation, once an initial and partial set of voltages are determined, the coefficients of the polynomial mapping are calculated and applied to calculate a new set of voltages. This process may be iterated, and in a preferred

embodiment, iterated two to three times. Further, the number of mirrors per iteration may also vary. In a preferred embodiment, the number of iterations in the first iteration is four and the number of iterations in the second iteration is sixteen.

FIG. 8 illustrates the calculated position coordinates for input mirror (1,1) to hit all 256 output mirrors for a given crossconnect design and the 4 measured positions, calculated from the voltage fine training data. In FIG. 8, the circles represent the theoretical spot diagram and the triangles represent the partial fine training result.

The calibration curve is updated with the new voltage versus position point. The raytracing program is also updated with the new mirror angle (position) versus beam position point. The iterated and updated calibration curve and raytrace are then used for subsequent measurements.

For a crossconnect 100 with two MEMS devices 10a, 10b, the transformation determination should be reciprocal, that is the process of transformation determination should be performed for each MEMS devices 10a, 10b. For a two-device example, the transformation data for each array must be determined, and then the transformation for operating each device is used to determine the voltages actually required to tilt the mirrors to the desired angle.

As described above, the transformation determination in the exemplary embodiment begins with two sets of data, one for each MEMS device 10a, 10b. A mapping is determined from a subset of the mirrors (one or more, but not a prohibitive number) from MEMS devices 10a to all mirrors from MEMS devices 10b and from a subset of the mirrors (one or more, but not a prohibitive number) from MEMS devices 10b to all mirrors from MEMS devices 10a. Then, an interpolation algorithm, such as a least squares fit algorithm, is applied to the two sets of transformation data to determine dx and dy offsets, a rotation offset, dθ, and a magnification m (collectively the “transformation”).

The next step is to reapply the transformation determination to the predictive calibration curve and/or the raytrace in order to obtain more accurate calibration curve and/or the raytrace information.

The present invention may be illustrated by the following example.

EXAMPLE

This example assumes two axes of rotation. The calibration curve of voltage versus position (along one axis) for each mirror is represented by:

$$X(V_{12}, V_{34}) = c_0 + c_1 V_{12} + c_2 V_{34} + c_3 V_{12} V_{34} + c_4 V_{12}^2 + c_5 V_{34}^2 + c_6 V_{12} V_{34}^2 + c_7 V_{12}^2 V_{34} + c_8 V_{12}^3 + c_9 V_{34}^3 \quad [1]$$

where

$$V_{12} = V_1 - V_2$$

$$V_{34} = V_3 - V_4 \quad [2]$$

$X(V_{12}, V_{34})$ =coordinates of ray for a pair of input and output mirrors c_n =polynomial coefficients.

The polynomial of Eq. (1) should be chosen to map the response curve of voltage versus position.

A similar formula can be written for a second axis. Data, as illustrated in FIG. 5, for each mirror 12a, 12b is measured in position space and then centered. The center is defined to be the position where $(V_{12}, V_{34})=(0,0)$. In this example, there are 169 data points. After the scan data is offset by the

center pixel values, the data is divided into four overlapping quadrant sets of 49 data points, representing the regions:

$$(x>0, y \geq 0), (x \geq 0, y \leq 0), (x \leq 0, y \geq 0), (x \leq 0, y \leq 0) \quad [3]$$

Each set of data points is converted into a 10 coefficient by 49 data point matrix. The coefficients c are calculated in Eq. (1) using singular value decomposition (SVD). In this way, an average deviation of less than 2 pixel units are obtained between the calculated and measured results using the polynomial relations. The above formulae provide a way to quickly calculate position from voltages. An inverse relation is used for the modeling to calculate voltages from position space. This is done using Newton method of root finding for the relation,

$$X(V_{12}, V_{34}) - X_0 = 0 \quad [4]$$

The scanning range of the voltages and positions should be wide enough to accommodate an actual design of the optical crossconnect.

Then, prediction data is calculated. Using a raytracing program, such as XEMAX or OSLO, or by geometric arguments, the position coordinates of the output mirror 12b can be modeled relative to the input mirror 12a, for each possible connection. The set of coordinates for each connection is calculated assuming zero offset, tilt and rotation between the MEMS devices 10a, 10b and any intervening optics. Using the relationship determined above, the voltages to make all the connections for all the mirrors 10a, 10b can be calculated. This first calculation gives a rough estimate of the voltages and should be refined when measurements are available. The first estimated voltages are used to make a subset of connections, such as a 4 by 4 subset, or 16 connections. The results from fine training are then used to calculate the transformation, which can be used to give a more accurate set of prediction voltages.

From the measured 16 connections, the voltages are converted back to position space using the fit polynomial for the 4 input 12a and output 12b mirrors. As discussed above, FIG. 8 illustrates the calculated position coordinates for input mirror (1,1) to hit all 256 output mirrors for a given crossconnect design and the 4 measured positions, calculated from the voltage fine training data.

The real data coordinates (triangles) are related to the theoretical coordinates (circles) by the following relationship.

$$\begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \\ 1 & x_4 & y_4 \end{bmatrix} \begin{bmatrix} a_x \\ b_x \\ c_x \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix}, \quad [5]$$

$$\begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \\ 1 & x_4 & y_4 \end{bmatrix} \begin{bmatrix} a_y \\ b_y \\ c_y \end{bmatrix} = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix},$$

where (x,y) are measured values and (X,Y) are calculated values. The coefficients a, b, c are mirror dependent and have the form,

$$\begin{aligned} a_{x,y}(r_{in}, c_{in}) &= A_a + B_a r_{in} + C_a c_{in} + D_a r_{in} c_{in} + E_a r_{in}^2 + F_a c_{in}^2, \\ b_{x,y}(r_{in}, c_{in}) &= A_b + B_b r_{in} + C_b c_{in} + D_b r_{in} c_{in} + E_b r_{in}^2 + F_b c_{in}^2, \\ c_{x,y}(r_{in}, c_{in}) &= A_c + B_c r_{in} + C_c c_{in} + D_c r_{in} c_{in} + E_c r_{in}^2 + F_c c_{in}^2, \end{aligned} \quad [6]$$

where r_{in} and c_{in} are rows and columns position of the input mirror 12a. A similar relationship is used for the output

mirrors **12b**. For the first four data points, because there are more unknowns than data points, only the values A, B, C can be calculated. When more data points are available, D, E and F can be calculated. Using SVD, the coefficients a, b, c are determined for the set of input and output mirrors **12a**, **12b**. Then, using the coefficients for the mirrors **12a**, **12b**, the global coefficients A, B, C etc. can then be calculated. Once the global coefficients are calculated, the new coordinates (x,y) for all possible input and output mirrors **12a**, **12b** are recalculated using the updated coefficients. The new coordinates are converted to voltage space and then begins to train the next 8x8 subsets of connections.

It is noted that the subsets should be well sampled and spread out. After the 8x8 connections are finished, new global coefficients and prediction values are calculated. For the next iteration, a 16x16 subset is trained and recalculated. In practice, after a 16x16 iteration, the predicted voltages should be very close to the actual voltages, such that a finite signal is obtained when the predicted voltage is applied.

After the first 4x4 measurement, the relationship between (x,y) and (X,Y) should be made nonlinear. This may be accomplished by adding quadratic terms such as

$$\begin{bmatrix} 1 & x_1 & y_1 & x_1 y_1 & x_1^2 & y_1^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_N & y & x_N y_N & x_N^2 & y_N^2 \end{bmatrix} \begin{bmatrix} a_x \\ b_x \\ c_x \\ d_x \\ e_x \\ f_x \end{bmatrix} = \begin{bmatrix} X_1 \\ \vdots \\ X_N \end{bmatrix}, \quad [7]$$

and the corresponding global coefficients.

$$\begin{aligned} d_{x,y}(r_{in},c_{in}) &= A_d + B_d r_{in} + C_d c_{in} + D_d r_{in} c_{in} + E_d r_{in}^2 + F_d c_{in}^2, \\ e_{x,y}(r_{in},c_{in}) &= A_e + B_e r_{in} + C_e c_{in} + D_e r_{in} c_{in} + E_e r_{in}^2 + F_e c_{in}^2, \\ f_{x,y}(r_{in},c_{in}) &= A_f + B_f r_{in} + C_f c_{in} + D_f r_{in} c_{in} + E_f r_{in}^2 + F_f c_{in}^2, \end{aligned} \quad [8]$$

For a large database of connections, the database should be checked. One technique of doing a self-consistent check is to look at the loss of each connection. In general, there are N² connections for an N port switch. There are further N loss values, which can be decomposed into input port loss and output port loss.

$$L_{total} = L_{input} + L_{output} \quad [9]$$

The average input/output port loss can be calculated directly from the database by inverting a 2NxN² matrix. For example, in case where N=2,

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{L_{input,1}} \\ \overline{L_{input,2}} \\ \overline{L_{output,1}} \\ \overline{L_{output,2}} \end{bmatrix} = \begin{bmatrix} L_{total,1,1} \\ L_{total,1,2} \\ L_{total,2,1} \\ L_{total,2,2} \end{bmatrix} \quad [10]$$

Inverting the matrix using SVD gives the average loss for each input and output. The database may then be verified by calculating the deviation of the average losses from the measured loss.

$$\frac{\Delta L}{L_{input} + L_{output}} = \frac{L_{total} - (\overline{L_{input}} + \overline{L_{output}})}{L_{input} + L_{output}}, \quad [11]$$

If the ratio is too large, for example greater than 10%, then there is a discrepancy and the connection should be retrained and/or examined (i.e. to clean the fiber and/or detector).

An advantage of the method of the present invention is that every mirror need not be tested or trained after the crossconnect **100** is assembled. This can reduce the time needed to align the crossconnect from days to hours.

It is noted that, in order to be most effective, the transformation should be determined from the mirrors or other elements that must tilt through the broadest range of angles (normally the corner elements, or the elements closest to the corners that work) are the elements that must tilt the most to make the desired connections.

It should be noted that the present invention is not limited to a gimbaled mirror configuration and is further applicable to modulator or a dynamic equalizer applications and a one axis configuration.

It is further contemplated that the manufacturer of the MEMS devices **10a**, **10b** may perform the calibration and raytracing step and a user of the assembled device may determine the transformation. Such a task division is contemplated as being within the scope of the present invention.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

What is claim is:

1. A method of calibrating a crossconnect including a MEMS device and another optical device, each of which further include a plurality of elements, said method comprising:

- (a) determining a relationship between an applied voltage and an angle response for a number of the elements of the MEMS device;
- (b) determining a function of beam position and element position for the number of the elements of the MEMS device;
- (c) assembling the MEMS device and the another optical device to produce the crossconnect;
- (d) applying voltages to make sample connections between the MEMS device and the another optical device based on the relationship and the function;
- (e) determining a transformation for the sample connections caused by packaging the crossconnect; and
- (f) redetermining the relationship and the function based on the transformation.

2. The method of calibrating a crossconnect of claim 1, wherein said step of determining a relationship between the applied voltage and the angle response includes a combination of measuring values and estimating values.

3. The method of calibrating a crossconnect of claim 2, wherein the estimated values are estimated using one of mathematical function fitting and interpolation.

4. The method of calibrating a crossconnect of claim 1, further comprising:

- determining the destination of a beam signal as a function of mirror position by performing raytracing.

5. The method of calibrating a crossconnect of claim 1, wherein the sample connections are made for corner elements.

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6. The method of calibrating a crossconnect of claim 1, wherein the transformation includes at least one of an x and y offset, a rotation offset, and a magnification.

7. The method of calibrating a crossconnect of claim 1, wherein at least one of the MEMS device and the another optical device are one of gimbaled mirror arrangements, non-moving elements, and optical fibers.

8. The method of calibrating a crossconnect of claim 1, further comprising iterating steps (a)–(f).

9. A crossconnect including a MEMS device and another optical device calibrated by the method of claim 1.

10. A method of preparing a MEMS device and another optical device for calibration as a crossconnect, the MEMS device and the another optical device each including a plurality of elements, said method comprising:

(a) determining a relationship between an applied voltage and an angle response for a number of the elements of the MEMS device; and

(b) determining a function of beam position and element position for the number of the elements of the MEMS device, wherein said step of determining a relationship between the applied voltage and the angle response includes a combination of measuring values and estimating values.

11. The method of calibrating a crossconnect of claim 10, wherein the estimated values are estimated using one of mathematical function fitting and interpolation.

12. The method of calibrating a crossconnect of claim 10, further comprising:

determining the destination of a beam signal as a function of mirror position by performing raytracing.

13. The method of calibrating a crossconnect of claim 10, further comprising:

determining a transformation for sample connections between the MEMS device and another optical device caused by packaging the crossconnect, wherein the transformation includes at least one of an x and y offset, a rotation offset, and a magnification.

14. The method of calibrating a crossconnect of claim 10, wherein at least one of the MEMS device and the another

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optical device are one of gimbaled mirror arrangements, non-moving elements, and optical fibers.

15. A method of calibrating a crossconnect including a MEMS device and another optical device, each of which further including a plurality of elements, said method comprising:

(a) applying voltages to make sample connections between the MEMS device and the another optical device based on a relationship between an applied voltage and an angle response for a number of the elements of the MEMS device and a function of beam position and element position for the number of the elements of the MEMS device;

(b) determining a transformation for the sample connections caused by packaging the crossconnect; and

(c) redetermining the relationship and the function based on the transformation.

16. The method of calibrating a crossconnect of claim 15, further comprising iterating steps (a)–(c).

17. The method of calibrating a crossconnect of claim 15, wherein the relationship between the applied voltage and the angle response includes a combination of measuring values and estimating values.

18. The method of calibrating a crossconnect of claim 17, wherein the estimated values are estimated using one of mathematical function fitting and interpolation.

19. The method of calibrating a crossconnect of claim 15, wherein the function of beam position and element position for the number of the elements of mirror position is obtained by raytracing.

20. The method of calibrating a crossconnect of claim 15, wherein the transformation includes at least one of an x and y offset, a rotation offset, and a magnification.

21. The method of calibrating a crossconnect of claim 15, wherein at least one of the MEMS device and the another optical device are one of gimbaled mirror arrangements, non-moving elements, and optical fibers.

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