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(54) METHODS AND APPARATUS FOR FABRICATING RADIATION REDISTRIBUTIVE DEVICES

(71) We, EASTMAN KODAK COMPANY, a Company organized under the laws of the State of New Jersey, United States of America, of 343 State Street, Rochester, New York 14650, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to methods and apparatus for fabricating radiation-redistributive devices such as projection screens, lighting reflectors, refractors, illumination aids for photographic prints, and traffic and advertising signs.

Heretofore, a wide variety of radiation-redistributive devices has been proposed to achieve such features as a definitely controllable field through which incident radiation is redistributed, uniform radiance throughout such field, high efficiency due to a definite separation of the field of redistribution from the environmental field and due to minimum absorption losses as the redistributing surface of such devices and a favourable rejection of radiation impinging on the device from sources other than those intended for irradiating the device.

In attempting to provide radiation-redistributive devices having one or more of the features mentioned above, two approaches have been taken. One approach is purely empirical in nature and involves the evaluation of commercially available, inherently reflective, refractive, or diffuse materials to determine the utility thereof for a particular application. Exemplary of the projection screens developed through such an empirical approach are the volume and surface diffuser-type rear projection screens, and the aluminum foil front projection screens disclosed in the commonly assigned U.S. Patent No. 3,408,132, high reflectance projection screens commercially available under the trademark Kodak Ektalite Projection Screen.

The second approach toward the provision of improved radiation-redistributive devices is analytical in nature, involving the derivation of mathematical expressions to define the contour which each elemental area of the redistributing surface must possess in order to achieve a desired redistribution of incident radiation, and the fabrication of an optical surface in accordance with such expressions. Lenticular projection screens and general lighting refractors are exemplary of such an analytical approach.

Notwithstanding the approach taken, radiation-redistributive devices heretofore proposed have not been totally satisfactory in all respects. Usually, certain desirable features are severely compromised to achieve other features which are deemed more desirable for a particular application. For instance, in the case of projection screens, several screens have been proposed having reflecting or refracting surfaces which, at least in theory, are capable of redistributing incident-image light in such a manner that the luminance of every elemental area on the screen surface is substantially constant throughout a predefined angular field of observation. Such screens, however, often suffer the disadvantages of being inefficient or wasteful of available image light and of being difficult, if not, for all practical purposes, totally impractical to

manufacture in large quantities. See, for instance, the screens disclosed in U.S. Patents 3,257,900 and U.S. 2,870,673. On the other hand, projection screens having highly efficient and readily manufacturable surfaces are often incapable of distributing incident image light uniformly and in a controlled manner, such surfaces commonly exhibiting substantial "hot spots" or regions of non-uniform luminance.

In accordance with the present invention there is provided a method of making a radiation-redistributive device having a radiation-redistributive surface defining a plurality of parallel rectilinear grooves, each groove varying in depth along its length in accordance with a predetermined waveform so that the device has a row of contiguous optical microelements in each groove; the method comprising the steps of:—

moving relatively to each other a cutting stylus of appropriate transverse cross-section and either a blank for the device or a pattern for the device, the relative movement involving a series of parallel traverses to cut sequentially the grooves or the pattern therefor respectively in the surface, modulating the stylus in a plane perpendicular to the surface in accordance with an electrical signal of the said predetermined waveform; and simultaneously modulating the stylus in the same plane in accordance with an electrical signal of random frequency and of an amplitude inversely proportional to the instantaneous frequency of the latter signal such that the optical micro-elements are of substantially uniform optical power.

A radiation-redistributive device or master in which the redistributing surface comprises a plurality of contiguous parallel grooves, each having a depth which varies along the groove length, can be economically fabricated using various equipment and techniques conventionally employed in the sound-recording industry. By mounting a sound-recording head in the tool holder of a conventional milling machine and by applying an electrical signal of appropriate amplitude and waveform to the input thereof, it has been found that the cutting stylus of the recording head can be used to cut precision contours in the surface of a workpiece as the workpiece and the stylus are moved relative to one another in a series of equally spaced, parallel traverses. Circuitry is provided for modulating the cutting position of the recording head stylus so as to cut optical micro-elements of such shape that, when irradiated by a source occupying a predefined position relative to the redistributive surface, substantially uniform radiance is produced throughout a prescribed field.

The cutting position of the stylus may be modulated in such a manner that, as contiguous grooves are cut in the surface of a blank master, the depth of each groove is caused to undulate at a random spatial frequency and thereby define alternately convex and concave optical micro-elements of random length but of substantially identical contour and optical power. Circuitry is provided for frequency-modulating a predefined stylus-driving signal with low-frequency noise, and for varying the depth of cut in accordance with the instantaneous frequency of the stylus-driving signal.

Thus there may be produced a projection screen comprising a plurality of contiguous optical micro-elements of random size but of similar image flux-distributing contour, a projection screen comprises a plurality of contiguous optical micro-elements of random size but of similar image flux-distributing contour. A screen surface comprising such randomly-sized micro-elements of common shape has been found to exhibit a velvet-like appearance under normal room light, one quite pleasing to the eye. Such a screen surface is fabricated by applying an appropriate electrical signal to the cutting stylus of a sound-recording head during the groove-cutting operation of the screen or screen master. To provide the appropriate electrical signal, circuitry is provided for frequency modulating the stylus driving signal with a noise signal, thereby producing optical micro-elements which vary randomly in length along the groove length, and for varying the amplitude of the frequency-modulated signal in such a manner that the depth (or height) of each micro-element remains proportional to the element length so that each micro-element, regardless of size, distributes incident image flux throughout the same solid angle (i.e., has the same optical power) as all other micro-elements.

Objects of the invention and its various advantages will become immediately apparent to those skilled in the art from the ensuing detailed description of preferred embodiments, reference being made to the accompanying drawings.

Figs. 1 and 2 are, respectively, diagrammatic representations of rear and front projection systems, respectively, illustrating the radiation-redistributing properties of rear and front projection screens embodying the invention;

Fig. 3 shows the ideal radiance curve for a radiation-redistributive device;

Figs. 4—6 illustrate a reflective radiation-redistributive device, structured in accordance with a preferred embodiment of the invention, in plan view and sections taken along lines 5—5 and 6—6, respectively;

Fig. 7 is a side elevational view of apparatus used in fabricating a master from which the radiation-redistributive devices of the invention can subsequently be replicated, such apparatus including a stereo sound-recording head;

Fig. 8 is a constructional diagram of the mechanism used to drive the cutting stylus of the sound recording head illustrated in Fig. 7;

Fig. 9 is a side elevational view of the cutting stylus and support therefor;

Fig. 10 is a front elevation of the cutting stylus illustrating the cutting profile thereof;

Fig. 11 is a perspective view of apparatus for supporting and moving a workpiece being operated on by the cutting apparatus illustrated in Fig. 7;

Fig. 12 illustrates the manner in which the waveform applied to the cutting stylus differs from the stylus motion produced thereby;

Fig. 13 is an electrical schematic of circuitry for driving the cutting stylus to produce one side of the radiation-redistributive surface illustrated in Figs. 4–6;

Fig. 14 illustrates the additional logic circuitry required to modify the circuit of Fig. 13 so as to produce the entire surface illustrated in Figs. 4–6;

Fig. 15 illustrates the manner in which the positive-going ramp of a sawtooth waveform is shaped to a desired the master;

Figs. 17—19 illustrate a radiation-redistributive device structured in accordance with another preferred embodiment of the invention, in plan view and in section taken along lines 18—18 and 19—19, respectively;

Fig. 20 is an electrical schematic of circuitry adapted to drive the cutting stylus in a manner such as to produce a master from which radiation-redistributive devices, such as that illustrated in Figs. 17—19, can be fabricated;

Fig. 21 is a block diagram of circuitry adapted to drive the cutting stylus of a sound recording head to achieve a master for making projection screen surfaces in accordance with the invention;

Fig. 22 is an electrical schematic of the phase lagging circuit of Fig. 21;

Fig. 23 is an electrical schematic of the amplitude compensation circuit of Fig. 21;

Fig. 24 is an electrical schematic of the shaping circuit illustrated in Fig. 21;

Fig. 25 is a magnified plan view of a fragmentary portion of a radiation-redistributive device of the type readily manufactured by the methods and apparatus of the present invention;

Figs. 26 and 27 are longitudinal and transverse sectional view of the device depicted in Fig. 25, taken along the section lines 3—3 and 4—4, respectively;

Fig. 28 is a scanning electron micrograph of a radiation-redistributive device fabricated in accordance with the method and apparatus of the invention; and

Fig. 29 is a photograph comparing the room light appearance of a projection screen surface structured in accordance with one embodiment of the present invention with a screen surface fabricated in accordance with another embodiment of the present invention.

As indicated above, the radiation-redistributive devices of the invention have utility in any situation wherein it is desirable or necessary to precisely control the redistribution or redirection of radiant energy from a surface which is irradiated by a source which occupies a predictable position relative to such surface. Such devices have been found to have particular utility as projection screens, both of the front and rear projection variety, being capable of presenting to a precisely definable audience area or field of observation a projected image of substantially uniform luminance, regardless of the viewing position within such audience area. Accordingly, projection screens and methods of making such screens represent preferred embodiments of the invention and the invention will be described hereinafter with particular reference thereto; however, it should be borne in mind that projection screens are merely exemplary of the uses for the invention.

The radiation-redistributing surface of the invention devices was derived mathematically based upon the theorems of geometrical optics and upon the following postulates which are believed to define a radiation-redistribution device having ideal radiation-redistributive properties:

(I) Every elemental area on the redistributing surface of the device shall redistribute all radiation incident thereon from an intended irradiating source throughout a solid angle just large enough to encompass a predefined field wherein the redistributed radiation has utility. (A radiation-redistributing surface satisfying this postulate is one of maximum efficiency, utilizing all available radiation).

(II) Every elemental area on the radiation-redistributing surface of the device shall redistribute incident radiation in such a manner that the radiance of every such area will be constant, no matter where measured within the solid angle through which radiation is redistributed. (With respect to projection screens, a surface satisfying this postulate is one which will present an image of uniform brightness

everywhere within the intended audience area, and no image whatsoever outside such audience area).

Referring now to Figs. 1 and 2, projection systems comprising projectors P and rear front projection screens S and S', respectively, are shown in two dimensions. Image light or flux emanating from the projector is focused upon the surfaces 10 of the projection screens, rear projection screen S being fabricated from a transparent material. As shown, each surface comprises a plurality of contoured optical mocroelements 11, shown, for purposes of illustration, greatly magnified and of concave shape. Actually, each microelement is preferably of a size so as to be unresolvable by the closest intended viewer having normal eyesight and viewing the screen without artificial aids, and can be either concave or convex in shape. The contour of each microelement is such that image flux incident thereon at an angle θ, measured from a line connecting the projector lens 15 to the screen centre C, is redistributed throughout a viewing angle H which is just large enough to encompass the predefined audience volume V. Viewing angle H consists of left and right viewing angles A and B, respectively, each being measured from a normal N to the screen surface. All angles are considered positive when measured in a counterclockwise direction from a normal to the screen surface. Because the size of the microelement is quite small relative to the distance separating the microelement from the projector, all light rays striking a particular microelement are assumed to be parallel.

It can be shown mathematically that to satisfy Postulates I and II above wherein the intended audience volume is bounded in either a transverse or longitudinal plane by audience angles A and B, every convex optical microelement comprising the radiation-redistributing surface must have transverse and longitudinal cross sections defined by at least a segment of the curve

$$(1)\quad u=\pm f(w;n)=\pm(\sqrt{1-w}(\sqrt{w}-2n)+\cos^{-1}\sqrt{w})$$

where n is the refractive index of the microelement (n being −1 when the microelement is reflective); u and w are the microelement coordinates, w being measured in a direction parallel to the path of the rays of radiation incident on the microelement and u being measured in the plane of the cross section, perpendicular to w; and w has a value within the following limits:

$\cos^2(A-\theta')\leq w\leq 1$, when f(w;n) is positive and the microelement refractive;

$\cos^2(B+\theta')\leq w\leq 1$, when f(w;n) is negative and the microelement refractive;

$\cos^2(B+\theta)\leq w\leq 1$, when f(w;n) is positive and the microelement reflective;

$\cos^2(A-\theta)\leq w\leq 1$, when f(w;n) is negative and the microelement reflective;

where θ is the projection in the u–w plane of the angles formed by a line connecting the microelement and projector, and the normal to the screen surface; and $n=\sin\theta/\sin\theta'$.

Similarly, it can be shown that every concave optical microelement comprising the projection screen surface must have transverse and longitudinal cross sections defined by at least a portion of the curve

$$(2)\quad u=\pm g(w;n)=\pm(\sqrt{1+w}(\sqrt{-w}-2n)+\cos^{-1}\sqrt{-w})$$

wherein w has a value within the following limits:

$-1\leq w\leq-\cos^2(B+\theta')$, when g(w;n) is positive and the microelement is refractive;

$-1\leq w\leq-\cos^2(A-\theta')$, when g(w;n) is negative and the microelement is refractive;

$-1\leq w\leq-\cos^2(A-\theta)$, when g(w;n) is positive and the microelement is reflective; and

$-1\leq w\leq-\cos^2(B+\theta)$, when g(w;n) is negative and the microelement is reflective.

Equations (1) and (2) above define the contour required for a microelement to provide an ideal goniphotometric response (i.e., constant radiance, between horizontal audience angles A and B, and vertical audience angles A' and B'. (See Fig. 3). As is apparent from these equations, screen performance is independent of the size and sense (concave or convex) of each microelement relative to adjacent ones. Thus, the microelements could be of random sizes and randomly sensed over the entire screen surface so long as the contours defined by Equations (1) and/or (2) are substantially met, such contours being dependent only on the angle at which incident light impinges the microelement surface, the horizontal and vertical audience angles through which such light must be distributed to encompass the intended audience area, and in the case of rear projection screens, the refractive index of the material from which the microelements are formed. For the most expedient manufacture of such a screen, the microelements should be substantially of the same size and be arranged in contiguous linear rows, each microelement having a transverse cross section which is everywhere curved in the same sense, preferably concave, and a longitudinal cross section which is shaped in an opposite sense from that of adjacent microelements in the same row. Thus, the preferred longitudinal cross section of each row of microelements is one which undulates from concave to convex, etc. Such a surface is illustrated in Figs. 4 through 6.

As shown in Figs. 4 through 6, a screen structured in accordance with the present invention comprises a surface which defines a plurality of contiguous linear grooves 16 shown running in a vertical direction from the top to the bottom edges of the screen. Where the edges of each groove intersect with those of adjacent grooves, cusp lines 17 are formed. The transverse cross section of each groove, as depicted in Fig. 5, is everywhere concave and is defined by Equation (2) above. The depth profile or longitudinal cross section of each groove, as illustrated in Fig. 6, alternately varies or undulates in shape from convex to concave, the convex and concave portions being defined by Equations (1) and (2), respectively. Thus, for each full wavelength of depth undulation, two microelements are formed, one concave and one convex. The longitudinal boundaries of each microelement are the lines 18 along which the sense of the depth profile changes from concave to convex, or vice versa. The lateral boundaries of each microelement are, of course, provided by cusp lines 17. As best shown in the sectional views of Figs. 5 and 6, the microelements are gradually "tilted" as their respective displacement from screen center C increases. The degree of such tilt is determined by the size and shape of the viewing area and, hence, the values of viewing angles A and B. The sense of such tilt (i.e., toward or away from the screen center) depends on whether the screen is reflective or refractive, reflective microelements being tilted toward the screen center, as shown in Figs. 5a, 5c, 6a, and 6c, and refractive microelements being tilted away from the screen center. Generally, the microelements are oriented with respect to each other such that the lines, formed by intersecting planes which bisect the horizontal and vertical angles through which each element distributes image light to the audience, substantially intersect at a common point in the audience area.

The photograph of Fig. 2g compares the room-light appearance of a projection screen surface 10 as above described, with a projection screen surface 10' structured in accordance with a preferred embodiment of the present invention. Surface 10 comprises a plurality of contiguous grooves of substantially uniform width which, as viewed in Fig. 1, run in a vertical direction. The depth of each groove undulates periodically along the groove length at a substantially constant spatial frequency, thereby defining a row of contiguous microelements of substantially equal half wavelength, alternating from concave to convex in shape along the groove length. The physical dimensions of each microelement are such as to be unresolvable by the closest intended viewer. Typically, microelement width and length vary from .001 to .010 inches, and the peak-to-peak groove depth is approximately .003 inches.

While the depth of each of the grooves comprising surface 10 undulates at the same spatial frequency, the phase of such undulations varies from groove to groove. And while such phase variation has been found to have substantially no adverse effect on screen performance, it has been found to give the screen surface a somewhat streaky appearance which is rather unpleasant aesthetically.

Projection screen surface 10' comprising the preferred form of the present invention, while having substantially the same light distributing qualities as surface 10, is substantially more pleasing aesthetically when viewed under normal lighting conditions, having a velvet-like appearance rather than the streaky appearance of surface 10. Screen surface 10', like surface 10, comprises a plurality of undulating contiguous grooves extending in a vertical

direction, as viewed in Fig. 1. However, unlike surface 10, the depth of the grooves comprising surface 10' does not vary at a substantially constant spatial frequency. Rather, the groove depth varies with a random wavelength, within a predefined range of wavelengths, to define optical microelements which randomly vary in size accordingly. Preferably, the range of microelement size is within approximately ±20% of a mean size. Moreover, unlike surface 10, the microelement depth (or height, depending on the sense of the microelement, concave or convex) is not uniform over screen surface 10'. Rather, the microelement depth varies in proportion to its length, so that each microelement, regardless of size, has a contour substantially defined by Equations (1) or (2) above and an optical power like all other microelements.

To fabricate the radiation-redistributive devices of the invention, it has been found that various equipment and techniques conventionally employed in the second recording industry can be used directly or in a modified form. In Fig. 7, apparatus used for cutting the radiation-redistributive microelements is illustrated in a side elevational view, being shown in a cutting position relative to a blank workpiece 20 wherein microelements are to be formed. While the microelements could be cut directly in any readily workable material which itself could be used as the radiation-redistributive device, the preferred method of manufacture comprises the fabrication of a master in some workable material, such as acetate or wax, from which a negative or press tool of correct contour can be subsequently made. The negative matrix can then be used to produce a multitude of positive radiation-redistributive devices by such well-known economical duplicating processes as stamping or embossing. Preferred methods of replicating radiation-redistributive devices from masters are described subsequently herein.

As shown in Fig. 7, the cutting apparatus comprises a conventional stereo sound recording head 30 which includes a cutting stylus S. While a monaural sound recording head could be used, a stereo head is preferred due to the high quality of conventional stereo heads and the auxiliary equipment available for such stereo heads. As in all sound recording heads, the cutting position of the stylus is determined by the waveform of an electrical signal applied to the recording head, such as through input cables 31. The recording head is mounted on a milling machine tool holder 32 by a cylindrical fitting 33. Means are provided for controlling the vertical position of fitting 33 in the tool holder 32 so as to provide a coarse, vertical adjustment of the recording head 30 above the workpiece. The workpiece may comprise, for instance, an acetate coating 37, the thickness of which is sufficient to receive the contours of the microelements being cut, the coating being formed on a supporting aluminium plate 36. Recording head 30 comprises a cutting assembly 40 having a horizontally extending support arm 41 which is slidably mounted on precision ways disposed in a saddle 42. By this arrangement, the horizontal position of cutting assembly 40 can be varied. Set screws 43a and 43b serve to lock arm 41 in a desired horizontal position. Saddle 42 is pivotally mounted about pin 44 disposed on recording head 30 so that the cutting stylus S, which forms a part of cutting assembly 40, can be moved into engagement with coating 37. The rotational movement of a cam 46 serves to raise and lower the stylus relative to the upper surface of coating 37 by contacting an arm 47 which is rigidly coupled with saddle 42. The downward force applied to the cutting assembly is controlled by screw 48 which serves to adjust the tension in spring 49. The precise depth of cut is controlled by adjustment screw 50 which varies the vertical distance of the stylus tip from a small glass ball follower 51 which rides on the uncut surface of coating 37 a short, horizontal distance away from the stylus.

A sound recording which has been found particularly well adapted for cutting projection screen masters is the Westrex Corporation, Model 3D Stereo Disc. As illustrated in Fig. 8 wherein a simplified constructional diagram of the mechanism which controls stylus movement is shown, each recording channel of the stereo recording head contains a magnetic coil form assembly 60, each of which contains a driving coil 62 located in separate pole pieces 64 and 65 which are attached to a single magnet 66.

The coil assemblies are attached to the stylus holder through links 68 which are stiff longitudinally, but flexible laterally. These links are braced in the centre to prevent excessive lateral compliance. This structure results in a stiff, forward driving system with a high compliance in the lateral direction.

The supporting member for the stylus is shown in Fig. 9. The use of a cantilever spring 70 permits the stylus to present a uniform impedance to complex motions in any direction in the vertical plane perpendicular to the drawing.

The cutting tip 72 of stylus S is preferably fabricated from sapphire or diamond, and is heated by heating coil 73 to a temperature such as to soften the acetate surface of the workpiece. If the surface described by the above equations were to be produced

exactly, it would be necessary to use a stylus having a different cutting profile for each groove cut. However, it has been found that when the intended audience area can be encompassed by audience angles of less than approximately ±40 degrees measured from the normal, the ideal screen surface can be satisfactorily approximated by using a single cutting stylus having a cutting profile defined by Equation (1) at $\theta=0$, and by tilting the stylus axis during the cutting operation so as always to be parallel to the plane which bisects the audience angle through which the groove being cut must distribute image flux to encompass the intended viewing area. The required curve is illustrated by the cutting profile of the stylus cutting tip 72 in Fig. 10, such curve being somewhat flattened relative to a half sinusoid.

In fabricating projection screen masters by use of the apparatus described above, the workpiece is moved relative to the heated cutting stylus in a series of equally spaced, parallel traverses. At the same time, the cutting position of the stylus is electronically varied relative to the workpiece surface to produce the desired longitudinal cross section or depth profile. Apparatus for moving the workpiece relative to the stylus is depicted in Fig. 11. As shown, such apparatus comprises a table 80 for supporting the workpiece during the cutting operation. Table 80 is preferably fabricated from a non-magnetic metal, such as aluminum, so as not to interfere with the magnetic cutting assembly 40. In the upper surface of table 80, a circular groove 85 is provided. At the base of groove 85 is an opening (not shown) which communicates with a nozzle 86 located on the edge of the table. Attached to nozzle 86 via hose 87 is a vacuum source (not shown). By this arrangement, the workpiece is securely fastened to the surface of table 80 by a vacuum coupling. Table 80 is mechanically secured to a movable workbed 88 comprising the x-y table 89 of a milling machine. Workbed 88 is movable in the x direction and its position is controlled with precision by a conventional stepping motor 90 which acts through lead screw 91. Workbed 88 itself rides on a carriage 93, also forming a part of the x-y table of the milling machine. Carriage 93 is movable in the y direction by a hydraulic pneumatic motor 95 which precisely controls the rate at which the table moves via piston rod 96.

To fabricate projection screen masters having transverse and longitudinal cross sections as depicted in Figs. 5 and 6, respectively, it is necessary to drive the cutting stylus with a signal, the waveform of which varies in accordance with the y-position of the stylus on the screen blank surface. Moreover, as mentioned above, it is also necessary to vary the angle at which the stylus contacts the screen blank in accordance with the x-position of the stylus on the workpiece surface.

To maintain the proper orientation between the cutting stylus and the workpiece during movement of the workpiece in the x direction, the milling machine tool holder is motorized so as to be capable of tilting the recording head in the x-z plane in accordance with an electrical input signal. The x-z position of the stylus is changed after each groove is cut so that at all times during the cutting operation the angle t between the longitudinal axis of the stylus and the work surface is:

$$t=\tan^{-1}(p/x)$$

where x is measured from the workpiece centre, and p is the projection in the x-z plane of the distance from the workpiece centre to the line at which the planes which bisect the requisite audience angles of the cut grooves substantially intersect. The motorized tool holder of the milling machine is controlled by the output of stepping motor 90.

To move the cutting stylus in a vertical plane and at a rate which, when the workpiece is moved at a constant rate relative thereto, results in the longitudinal cross section or depth profile desired, the same signal must be applied, 180° out of phase, to both drive coils 62. Moreover, since the stylus is not mounted for pure vertical movement, but rather for pivotal movement on the cantilever spring 70, so as to traverse an arcuate path as shown in phantom lines, it is necessary to drive the stylus with a somewhat different waveform than that which corresponds to the longitudinal cross section desired. Referring to Fig. 12, when a waveform 101 is applied to the cutting stylus, the resulting groove has a depth profile as shown by the asymmetrical waveform 102. To compensate for the asymmetry, it is necessary to drive the cutting stylus with a counterbalancing asymmetrical waveform 103 which the arcuate stylus movement converts to the depth profile desired (e.g., waveform 101). It is interesting to note that in the sound recording art, such asymmetry is automatically compensated for during playback by the pickup stylus, which is also pivotally mounted and moves along an arcuate path similar to that along which the stylus which cut the original master moved. In achieving a desired profile in projection screens, however, such asymmetry must be compensated for by circuitry for modifying the desired waveform accordingly.

Circuitry for driving the cutting stylus to

produce a depth profile such as illustrated in Fig. 5 is illustrated in Figs. 13 and 14. To facilitate an understanding of the circuitry, only that portion which is used to cut half of the screen master, either the upper or lower half, is initially described. The additional logic circuits required to cut the entire screen are illustrated in Fig. 14.

In Fig. 13, circuitry is disclosed for generating the electrical waveform whereby the cutting stylus can be modulated to produce microelements having depth profiles similar to those illustrated in Figs. 5a and 5b. It has been found that the required electrical waveform can be achieved by adding a sawtooth waveform, in varying amounts depending upon the y-position of the cutting stylus, to the asymmetrical waveform required for producing the desired depth profile at the screen centre (y=0). To generate the necessary sawtooth waveform, a sawtooth generator 130 is provided, such generator comprising a flip-flop 131, a limit detector 132, resistor R_1 and R_2, diode D1, capacitor C1 and operational amplifier A1. Amplifier A1 is connected as an integrator to give a linear ramp while the voltage at q, V_q, is constant. When V_q is negative, the ramp output V_s of the sawtooth generator is positive-going. When V_s exceeds the positive threshold of limit detector 132, the flip-flop 131 is switched to make V_q positive, at which time V_s becomes negative-going. When V_s reaches a negative limit, the flip-flop is again switched, to make V_q negative again. Operational amplifier A1 preferably has complementary outputs, and the limit detector 132 acts by detecting the negative limit of first one output and then the other. The slopes of the positive- and negative-going ramps of the sawtooth are controlled by diode D1 and resistors R1 and R2, the latter being variable. Diode D1 is non-conducting when V_q is negative, and conducts only when V_q is positive. Therefore, the positive-going ramp is slower than the negative-going ramp because the slope of the former is determined by the current flowing through resistor R1 only, whereas the slope of the latter is determined by the current flowing through both resistors R1 and R2. By varying the value of resistor R2, the slope of the negative-going ramp can be varied.

The sawtooth output of generator 130 is then fed through a non-linear shaping circuit 140 which, as shown in Fig. 15, acts to convert the linear ramp 141 to the asymmetrical waveform 142 required to drive the cutting stylus to achieve the desired shape of the microelements at the screen center. To prevent that portion of the shaping circuit output which occurs during the flyback (fast-sloped negative-going ramp) of the sawtooth from being applied to the cutting stylus, a blanking gate 143 is provided which transmits the input signal from the shaping circuit only when V_q is negative (i.e., during the slow ramp). The output of the shaping circuit 140 produces a depth profile for the screen elements at y=0. To produce the required depth profile as the y-position of the cutting stylus gradually increases, it is necessary to gradually "tilt" the y=0 depth profile. Such gradual tilting is accomplished by gradually adding, as the y-position of the cutting stylus gradually increases, the sawtooth waveform V_s to the output of the shaping circuit 140. Such addition is accomplished by operational amplifier A2. To vary the contribution of the sawtooth waveform, resistor R3 is mechanically varied by the y-position of the milling machine carriage. In Fig. 16, the output f of the amplifier A2 is illustrated when the cutting stylus is in a position displaced along the y axis from the screen centre.

To provide an electrical waveform whereby the cutting stylus can be modulated in such a manner as to properly vary the groove depth on both sides of the screen centre, it is necessary to provide circuitry for interchanging the direction of the fast and slow slopes of the sawtooth (i.e., change the sense of the sawtooth) as the cutting stylus passes through the centre of the screen. Moreover, it is necessary to switch the shape-blanking so that gate 143 operates during the fast-sloped portion of the sawtooth, whether positive or negative-going. The required circuitry is illustrated in Fig. 14. To switch the sense of the sawtooth at y=0, the fast-sloped diode D1 of Fig. 13 is replaced by an "exclusive OR" gate 150, the output of which is controlled by a flip-flop 151. The output of flip-flop 151 is controlled by a switch on the milling machine carriage, switching from one state to another as the screen centre (y=0) passes the cutting stylus. To properly cut both sides of the screen surface, it is necessary to provide an additional shaping circuit 152 since the asymmetry caused by the arcuate movement of the cutting stylus does not depend on the particular portion of the screen being cut. The output of the proper shaping circuit is supplied to amplifier A2, during the slow ramp portion of the output of the sawtooth generator, through blanking gates 143 and 153 which are controlled respectively by NAND gate 155 and OR gate 156.

In Fig. 21, preferred circuitry for driving the cutting stylus in such a manner as to randomly vary the size of the microelements cut thereby, without disturbing the ability of such elements to distribute image light uniformly throughout a common solid

audience angle, is illustrated in block diagram form. Speaking in terms of Fourier analysis, the signal applied to the driving coils of the cutting stylus to produce grooves having a depth profile defined by the equations above is rich in harmonics. Therefore, if the signal is to pass with undistorted shape through the audio amplifier of the recording head, its fundamental frequency must lie near the lower end of the flat part of the pass-band of the amplifier, but not so low as to become subject to the phase distortion associated with the low-frequency cutoff characteristic. For this reason, the median frequency of the wave generator 100 used to generate the basic sinusoidal waveform from which the stylus driving signal is ultimately derived was chosen to be 200 Hz, and it follows then that the length of the microelements is determined by the rate at which the screen blank is moved in the y-direction past the cutting stylus. In order to randomly vary the size of each microelement by ±20% of a mean size, the frequency of the signal applied to the cutting stylus must be randomly varied by ±20% about 200 Hz, or from 160 to 240 Hz. To produce such random variation, the output of the sine wave generator 100 is frequency modulated by a noise signal. Such a noise signal is provided by a conventional noise generator 104, the output of which is fed through a low-pass filter 106 having a cutoff frequency of about 20 Hz. The dc component of the noise signal is eliminated by capacitor C1. The amplitude of the noise generator 104 is set so that the frequency excursions of the cutting signal are confined almost entirely within the limits of ±20% of the centre frequency of 200 Hz. After passing through a buffer amplifier A1, the low frequency noise is applied to the sine wave generator. Generator 100 is of the type which provides an output frequency based upon the amplitude of an input voltage.

If the frequency of the cutting signal were altered while the amplitude thereof remained constant, the contour of each microelement would vary along the groove length, and each microelement would distribute image light over wide audience angles determined by its particular contour. In order to maintain the optical power of each microelement constant, regardless of its size, it is necessary to change the amplitude of the cutting signal in concert with its frequency, in such a manner that the amplitude is always proportional to the wavelength of the cut, or inversely proportional to the cutting-signal frequency. This implies that the cutting-signal amplitude must be under the control of the same modulating (noise) signal that frequency-modulates the output of generator 100. Thus, the output of the noise generator is also applied to an amplitude compensation circuit 105, described in detail herein below.

As indicated above, in order to drive the cutting stylus in such a manner as to cut symmetrical microelements along the groove length, it is necessary to apply an asymmetrically distorted waveform to the driving coils of the cutting stylus which, due to the arcuate movement of the stylus, is converted into the desired groove-cutting stylus movement. It has been found that the required asymmetry can be substantially achieved by adding to the sinusoidal output of generator 100 a small amount of its second harmonic, in phase with the fundamental frequency. A conventional squaring circuit 110, comprising an analog multiplier module having the same signal applied to both inputs, is used to generate the second harmonic waveform (sin 2x) from the fundamental. Capacitor C2 serves to eliminate the dc component of the output of circuit 110 which is $(\sin x)^2$. Since the midpoint of the resulting waveform lags the sin x waveform by 45°, it is necessary to feed the output of the wave generator through a phase-lagging circuit 113 before combining it with the second harmonic signal in summing operational amplifier A5. The output of the summing amplifier A5 is then fed through a shaping circuit 120 which converts the asymmetrical output of the summing amplifier A5 to the asymmetrical waveform required to drive the cutting stylus. The output of the shaping circuit 120 is then fed to the amplitude compensating circuit 105 which acts to vary the amplitude of the shaping circuit output to a level inversely proportional to its instantaneous frequency. The output of the amplitude compensation circuit 105 is then applied to both input channels of the stereo sound-recording amplifier.

When the output frequency of generator 100 is constant, the phase lag of 45° which is required of circuit 113 can be accomplished by a simple RC circuit. However, when the output of generator 100 is frequency modulated, such as by the noise generator 104, the reactance of the capacitor varies with the instantaneous frequency, according to the formula $X_c = 1/2\pi fC$. This means that, as the frequency varies, both the phase lag and the amplitude of the output vary. To solve this problem, a constant reactance phase-lagging circuit was devised, such circuit being illustrated schematically in Fig. 22.

As mentioned hereinbefore, the output frequency of wave generator 100 varies in accordance with the noise voltage V_n from amplifier A1. As shown in Fig. 22, the out-

put of the wave generator is applied to the phase-lag circuit which comprises resistor R10 and capacitor C2. Operational amplifier A4 is a high-input-impedance unity-gain isolation amplifier which ensures that the action of the phase-lag circuit is not altered by reason of being loaded by resistor R11 and the input impedance at terminal Z of module M-1. Module M-1 is an analog divider, which acts as an amplifier having a voltage gain, from Z to X, which can be varied under the control of an electrical signal applied to terminal Y.

Connected as shown in Fig. 22, module M-1 causes the effective value of capacitor C2 to be larger than its actual value. Varying the gain of Module M-1 results in a corresponding change in the effective value of the capacitance of C1. The gain-control signal for Module M-1 is obtained by adding a constant voltage to the modulating noise voltage in operational amplifier A3. In the preferred embodiment, resistors R7, R8, and R9 are selected to make the output of amplifier A3 approximately $-(3+3.9\ v_n)$ volts, when the instantaneous frequency of the wave generator is 200 $(1+v_n)$ Hz.

In accordance with the Fig. 22 circuit, the effective value of the capacitance is varied in concert with the output frequency of the wave generator 100 in such a manner that effective reactance X_c of capacitor C2 has a maximum change of only 1.6% while v_n varies over the range of ±0.2 volts, and the output frequency of wave generator 100 varies between 160 and 240 Hz. An uncompensated capacitor would change its reactance over a total range of 41.7% of its median value for the same frequency changes. Thus, the effect of the constant reactance circuit of Fig. 8 is to hold the phase shift and the amplitude of the output of amplifier A4 substantially constant while the wave generator frequency varies under the influence of the noise voltage. To vary the amount of second harmonic added to or subtracted from the output of amplifier A4, a potentiometer P1 is connected as shown.

In order for the cutting stylus to cut microelements of random size but of similar contour, it is necessary to vary the amplitude of the variable-frequency output of shaping circuit 120 so that the product of amplitude and frequency is substantially constant. As shown in Fig. 23, the output of shaping circuit 120 is fed to input terminal Z of an analog divider module M-3. Output X of the module M-3 is proportional to Z/Y. The noise voltage v_n from buffer amplifier A1 is fed to operational amplifier A2 which adds a constant voltage to it so that the output of amplifier A2 is proportional to $-(1+v_n)$ and therefore also proportional to the instantaneous frequency of the wave generator. The output of amplifier A2 is then fed to input terminal Y of module M-3 which serves to divide the instantaneous amplitudes of the input signals so as to provide an output, the amplitude of which is inversely proportional to frequency. The frequency applied to terminal Z increases, as the amplitude of the signal (of negative polarity) applied to terminal Y increases.

To produce the desired waveform from the asymmetrically distorted sine wave output of summing amplifier A5, output of the amplifier is fed to the shaping circuit 111. As shown in Fig. 24, this signal is segmented by reason of having to overcome successively the forward voltage drops across diodes D1—D10. Diodes D1—D5 and D6—D10 serve to segment the positive and negative-going portions of the input signal, respectively. Operational amplifier A6 serves to sum the contributions of the various segments to produce a difference signal Ax having a waveform representing the difference by which the desired waveform [Equation (2) plus distortion] differs from the asymmetrically distorted sine wave. The contributions of the individual segments to the output of amplifier A6 are adjusted by varying the values of resistors R-14 to R-18. The output of amplifier A6 is adjustable in amplitude by potentiometer P2. By simply adding the difference signal Ax, which is of a polarity opposite that of the unshaped signal due to the polarity reversing effect of amplifier A6, to the unshaped signal, the desired waveform for driving the cutting stylus is achieved. Such addition is performed by operational amplifier A7. Resistors R19 and R20 and potentiometer P3 serve to control the gain provided by the summing amplifier A7. The output of amplifier A7 is then fed to the input to the analog divider module M-3 of the amplitude compensation circuit.

To initiate the cutting operation, a start button is pressed which pivots the cutting assembly 40 about pin 44 into a cutting position, causes the hydraulic-pneumatic motor 95 to move the milling machine carriage in the y direction and causes the above-described electronic circuitry to drive the cutting stylus according to the waveform of the electrical signal applied thereto. After cutting a groove of predetermined length, a microswitch (not shown) is actuated by carriage 93 which serves to stop pneumatic motor 95, activate a solenoid which moves cam 46 of the recording head clockwise into a position to pivot the cutting assembly into an inoperative position, and actuate stepping motor 90 so as to move workbed 88 a predetermined distance in the x direction. The microswitch also returns the milling machine carriage to its starting position on the y-axis which, in turn, actuates a second

microswitch. When actuated, the second microswitch rotates cam 46 counterclockwise to permit the recording head to pivot into an operable cutting position, and the cutting process is repeated. This process continues without interruption until the entire screen master has been cut.

As the heated stylus S cuts a groove in the acetate coating, a continuous sliver or chip is extricated from the workpiece surface. To continuously draw this sliver away from the workpiece, a vacuum nozzle 162 (shown in Fig. 7) connected to a vacuum source through hose 163, is positioned adjacent stylus S during the cutting operation. The maximum depth of cut produced by the stylus in the acetate coating is controlled by ball follower 51 which, as mentioned hereinabove, rides on an uncut portion of the coating, near the stylus. The recording head includes a mechanism for maintaining the distance between the stylus tip and the base of the ball constant. Preferably, the groove spacing and minimum groove depth are set such that no "land" or flat areas exist between adjacent grooves.

Another projection screen embodying the present invention is illustrated in Figs. 17—19 and is generally designated by the reference numeral 200. Like the aforedescribed screen, the surface of screen 200 comprises a plurality of contiguous microelements having boundaries defined in a transverse direction by cusp lines 201 formed by the intersecting edges of adjacent linear grooves 202, and in a longitudinal direction by periodic shifts occurring along lines 203 in the groove depth profile from concave to convex. However, unlike the aforedescribed screen, the contour of all microelements comprising the surface of screen 200 is substantially identical, each being contoured such as to uniformly distribute (i.e., distribute with constant luminance) normally incident image light throughout the same horizontal and vertical audience angles. Each microelement has transverse and longitudinal cross sections defined by the above equations. In order to satisfy Postulate I set forth above, namely that each elemental area on the screen surface distribute image light only throughout an angle just large enough to encompass a predefined viewing area, it is necessary to orient each microelement on the screen surface such that the planes which bisects its vertical and horizontal audience angles intersects with similar bisecting planes of all other microelements at a point remote from the screen surface. Preferably, such orientation is accomplished by giving the screen surface a substantially spherical shape, the centre of spherical curvature corresponding to the desired point of intersection of the optical axes of the microelements.

Rather than curving the screen surface to effectively adjust the orientation of each microelement, Postulate I could be satisfied by adjusting the angle at which image light impinges upon each microelement. Such adjustments could be accomplished in the case of a rear projection screen by providing the rear surface 205 of the projection screen, that is, the surface closest to the projector, with a Fresnel-like lens. Obviously, combinations of Fresnel lenses and other screen curvatures, such as cylindrical, could be used.

To fabricate screens of the type illustrated in Figs. 17—19, a flat master is initially made using the techniques and apparatus described above. From the master, a flexible negative matrix is made, which may be subsequently curved and used to generate correspondingly curved positive projection screens by the molding techniques described hereinbelow.

In fabricating the master, both channels of the above-described stereo sound recording head are fed electrical waveforms defined by Equations (1) and (2) above, at $\theta=0$. In Fig. 20, electronic circuitry is schematically illustrated for generating the required waveform. As previously indicated, such waveform differs from a true sine wave in that the peaks are flattened, relative to the lower-amplitude portions of the wave. Moreover, as also mentioned hereinabove, to produce a groove depth profile in accordance with a desired waveform, it is necessary to drive the cutting stylus with an asymmetrical waveform which is converted to the desired waveform by the arcuate stylus movement. To produce the waveform required, the output (sin x) of a conventional sinewave generator 209 is first asymmetrically distorted by asymmetrical circuit 210 to compensate for the arcuate stylus movement, and then shaped by shaping circuit 211 to produce the waveform required for appropriately driving the cutting stylus S. It has been found that by adding to the sine waveform a small amount of its second harmonic, the requisite asymmetrical distortion can be achieved. A squaring circuit 212, such as an analog multiplier module, is used to generate the second harmonic waveform (sin 2x) from the fundamental. Capacitor C2 is used to eliminate the dc component of the squaring circuit output so as to produce a positive- and negative-going signal. Since the midpoint of the resulting waveform lags in the sin x waveform by 45°, it is necessary to feed the output of the sine wave generator through a simple RC phase-lagging circuit 213. In this manner, the two waves are

added while in phase by operational amplifier A3. The amount of asymmetry in the output of amplifier A3 depends, of course, on the peak-to-peak amplitude of the added second harmonic. Potentiometer P1 serves to vary the second harmonic amplitude prior to being added to the fundamental.

To produce the desired waveform from the asymmetrically distorted sine wave output of circuit 210, such output is fed to the shaping circuit 211. The input signal to shaping circuit 211 is segmented by reason of having to overcome successively the forward voltage drops across diodes D3—D12. Diodes D3—D7 and D8—D12 serve to segment the positive- and negative-going portions of the input signal, respectively. Operational amplifier A4 serves to sum the contributions of the various segments to produce a difference signal Δx having a waveform representing the difference by which the desired waveform differs from the asymmetrically distorted sine wave input. The contributions of the individual segments to the output of amplifiers A4 are adjusted by varying the values of resistors R5—R9. The output of amplifier A4 is adjustable in amplitude by potentiometer P2. Resistors R10 and R11 and potentiometer P2 serve to control the gain of amplifier A5. By simply adding the difference signal Δx, which is of a polarity opposite that of the unshaped signal due to the polarity reversing affect of amplifier A4, to the unshaped signal, the desired waveform for driving the cutting stylus is achieved. Such addition is performed by operational amplifier A5. Resistors R10 and R11 and potentiometer P3 serve to control the gain provided by the summing amplifier A5. The output of amplifier A5 is then used as the inputs to both driving coils of the stereo recording head to drive the cutting stylus.

After making the projection screen masters in accordance with the aforedescribed methods and apparatus, projection screens can be produced therefrom by making a negative matrix or master from the original, and casting positive screens, in a resinous material, from the negative master. Preferably, the negative master is made from General Electric RTV-60 silicone rubber which is prepared by adding three grams of dibutyl tin dilaurate RTV curing catalyst to two pounds of the RTV-60 rubber, agitating the mixture with an electric stirrer for five minutes and then placing it in a bell jar which is then evacuated to a pressure of 150 microns of mercury for about twenty minutes. Upon fixing sidewalls to the edge of the original master, the RTV rubber mixture can then be poured into this mold so that no air is entrapped. After curing, the rubber mould can then be used to cast projection screens.

The apparatus and methods set forth above are designed to produce planar projection screen surfaces comprising contiguous optical microelements which are of uniform size, or are of random size within a predefined size range (determined by the amplitude of the noise voltage, if used), and are of substantially identical contour. Moreover, the orientation of each of the microelements is such that its optical axis is substantially parallel to the axes of all other microelements. By controlling the angle at which incoming image-light impinges on each microelement, such as by curving the redistributive surface (in the case of a front or reflection-type projection screen) or by using the surface in conjunction with a Fresnel-like lens (in the case of a rear or refraction-type projection screen) screen efficiency can be substantially enhanced. Since the solid angle through which each microelement redistributes image-light is a function of its angle of incidence on the microelement surface, proper selection on the angle of incidence can be used as a means for directing the redistributed image-light from each microelement toward the audience space.

To fabricate spherically or otherwise curved front projection screens of the type depicted in Figs. 17—19, the rubber negative mould is disposed on an appropriately curved support prior to casting. A Maraglass resin, after being degassed, is then poured into the mould. After heating in an oven at 200°F for several hours to harden the resin, the casting is to be coated with aluminium to form a front projection screen. Refractive or rear projection screens can be made from a planar master by incorporating a Fresnel-like lens on the castings replicated therefrom.

The device of Fig. 25 is comprised of a plurality of contiguous grooves 10, the depth of which continuously varies along the groove length in a periodic symmetrical manner, as best illustrated in Fig. 26. As shown in Fig. 27, the transverse cross section of the grooves depends only upon the groove depth where taken; that is, when taken at equal depths, the transverse cross section is the same from groove to groove. As the depth of each groove varies along its length, in accordance with a predetermined periodic waveform, optical microelements 11 are defined every one-half wavelength of the waveform, such microelements alternately varying from concave to convex. Where adjacent grooves meet, cusp lines 12 are formed. The width W of each microelement is, of course, determined by

the groove width or the distance between adjacent cusp lines 12. The length L of each microelement is measured between points d, representing the average groove depth or the points at which the sense of the groove profile changes from concave to convex, or vice versa. When the device is employed as a projection screen, the size of each microelement is preferably too small to be resolved by the closest intended view; e.g., 10^{-4} square inches.

A scanning electron micrograph of a portion of a screen master fabricated with the apparatus and method set forth hereinabove is provided in Fig. 28. As is apparent, the spatial frequency of the grooves is substantially less than that of the depth variations. The fact that the depth profiles are not perfectly in phase from groove to groove has been found to have no substantial effect on screen performance.

As indicated above front and rear projection screens merely constitute a preferred embodiment of the invention and it should be understood that other radiation-redistributive devices, such as those already mentioned, as well as the many obvious variations and modifications of the invention as described, are considered within the scope of the invention as defined in the appended claims.

Radiation redistributive devices are claimed in Patent Application No. 57517/72 (Serial No. 1421138) from which the present application has been divided.

WHAT WE CLAIM IS:—

1. A method of making a radiation-redistributive device having a radiation-redistributive surface defining a plurality of parallel rectilinear grooves, each groove varying in depth along its length in accordance with a predetermined waveform so that the device has a row of contiguous optical microelements in each groove; the method comprising the steps of:—

moving relatively to each other a cutting stylus of appropriate transverse cross-section and either a blank for the device or a pattern for the device, the relative movement involving a series of parallel traverses to cut sequentially the grooves or the pattern therefor respectively in the surface, modulating the stylus in a plane perpendicular to the surface in accordance with an electrical signal of the said predetermined waveform; and simultaneously modulating the stylus in the same plane in accordance with an electrical signal of random frequency and of an amplitude inversely proportional to the instantaneous frequency of the latter signal such that the optical microelements are of substantially uniform optical power.

2. A method as claimed in Claim 1, wherein the cutting stylus is arranged to cut the said grooves in a plane surface of a blank for the device, and wherein the optical microelements are cut differently in accordance with their relative position on the device.

3. A method as claimed in Claim 1, wherein the cutting stylus is arranged to cut the said grooves in a plane surface of a pattern for the device, the method including the steps of forming a negative mould from the pattern and of moulding the device from the negative mould.

4. A method as claimed in Claim 3, including the steps of curving the negative mould in predetermined manner, and of moulding the device therefrom.

5. Apparatus for use in performing the method of Claim 1, comprising groove cutting means including a stylus of the said transverse cross-section, control means responsive to an electrical signal for varying the cutting position of the stylus, means for moving the blank for the device or the pattern for the device relatively to the stylus so that grooves can be cut in a surface thereof, means for applying an electrical signal of the said predetermined waveform to the control means and for simultaneously applying thereto an electrical signal of random frequency and of an amplitude inversely proportional to the instantaneous frequency of the latter signal.

6. Apparatus as claimed in Claim 5, wherein the said means for moving is arranged to move the blank for the device or the pattern for the device relatively to the stylus at a substantially constant velocity.

7. Apparatus as claimed in Claim 5, wherein the means for applying the said electrical signals to the control means comprises a voltage-controlled sine-wave generator and noise means operatively coupled to this sine-wave generator for randomly varying the frequency of the sinusoidal output thereof.

8. Apparatus as claimed in Claim 7, wherein the said applying means further comprises means for asymmetrically distorting the sinusoidal output of the said sine-wave generator.

9. Apparatus as claimed in Claim 8, wherein the said applying means further comprises means operatively coupled to the said distorting means and the said noise means for varying the amplitude of the asymmetrically distorted output of the said distorting means in a manner inversely proportional to the instantaneous frequency of the said distorting means output.

10. A radiation-redistributive device formed from a blank by the method of Claim 1 or Claim 2.

11. A radiation-redistributive device

the groove width or the distance between adjacent cusp lines 12. The length l, of each microelement is measured between points d, representing the average groove depth or the points at which the sense of the groove profile changes from concave to convex, or vice versa. When the device is employed as a projection screen, the size of each microelement is preferably too small to be resolved by the closest intended view; e.g., 10^{-4} square inches.

A scanning electron micrograph of a portion of a screen master fabricated with the apparatus and method set forth hereinabove is provided in Fig. 28. As is apparent, the spatial frequency of the grooves is substantially less than that of the depth variations. The fact that the depth profiles are not perfectly in phase from groove to groove has been found to have no substantial effect on screen performance.

As indicated above front and rear projection screens merely constitute a preferred embodiment of the invention and it should be understood that other radiation-redistributive devices, such as those already mentioned, as well as the many obvious variations and modifications of the invention as described, are considered within the scope of the invention as defined in the appended claims.

Radiation redistributive devices are claimed in Patent Application No. 57517/72 (Serial No. 1421138) from which the present application has been divided.

WHAT WE CLAIM IS:—

1. A method of making a radiation-redistributive device having a radiation-redistributive surface defining a plurality of parallel rectilinear grooves, each groove varying in depth along its length in accordance with a predetermined waveform so that the device has a row of contiguous optical microelements in each groove; the method comprising the steps of:—

moving relatively to each other a cutting stylus of appropriate transverse cross-section and either a blank for the device or a pattern for the device, the relative movement involving a series of parallel traverses to cut sequentially the grooves or the pattern therefor respectively in the surface, modulating the stylus in a plane perpendicular to the surface in accordance with an electrical signal of the said predetermined waveform; and simultaneously modulating the stylus in the same plane in accordance with an electrical signal of random frequency and of an amplitude inversely proportional to the instantaneous frequency of the latter signal such that the optical microelements are of substantially uniform optical power.

2. A method as claimed in Claim 1, wherein the cutting stylus is arranged to cut the said grooves in a plane surface of a blank for the device, and wherein the optical microelements are cut differently in accordance with their relative position on the device.

3. A method as claimed in Claim 1, wherein the cutting stylus is arranged to cut the said grooves in a plane surface of a pattern for the device, the method including the steps of forming a negative mould from the pattern and of moulding the device from the negative mould.

4. A method as claimed in Claim 3, including the steps of curving the negative mould in predetermined manner, and of moulding the device therefrom.

5. Apparatus for use in performing the method of Claim 1, comprising groove cutting means including a stylus of the said transverse cross-section, control means responsive to an electrical signal for varying the cutting position of the stylus, means for moving the blank for the device or the pattern for the device relatively to the stylus so that grooves can be cut in a surface thereof, means for applying an electrical signal of the said predetermined waveform to the control means and for simultaneously applying thereto an electrical signal of random frequency and of an amplitude inversely proportional to the instantaneous frequency of the latter signal.

6. Apparatus as claimed in Claim 5, wherein the said means for moving is arranged to move the blank for the device or the pattern for the device relatively to the stylus at a substantially constant velocity.

7. Apparatus as claimed in Claim 5, wherein the means for applying the said electrical signals to the control means comprises a voltage-controlled sine-wave generator and noise means operatively coupled to this sine-wave generator for randomly varying the frequency of the sinusoidal output thereof.

8. Apparatus as claimed in Claim 7, wherein the said applying means further comprises means for asymmetrically distorting the sinusoidal output of the said sine-wave generator.

9. Apparatus as claimed in Claim 8, wherein the said applying means further comprises means operatively coupled to the said distorting means and the said noise means for varying the amplitude of the asymmetrically distorted output of the said distorting means in a manner inversely proportional to the instantaneous frequency of the said distorting means output.

10. A radiation-redistributive device formed from a blank by the method of Claim 1 or Claim 2.

11. A radiation-redistributive device

formed from a pattern by the method of Claim 1 or Claim 3 or Claim 4.

12. Apparatus for fabricating a radiation-redistributive device, as claimed in Claim 5 and substantially as hereinbefore described with reference to the accompanying drawing.

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