

Oct. 26, 1965

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3,214,682

LOW-LOSS HALL-EFFECT DEVICES

Filed Sept. 26, 1961

3 Sheets-Sheet 1

FIG. 1

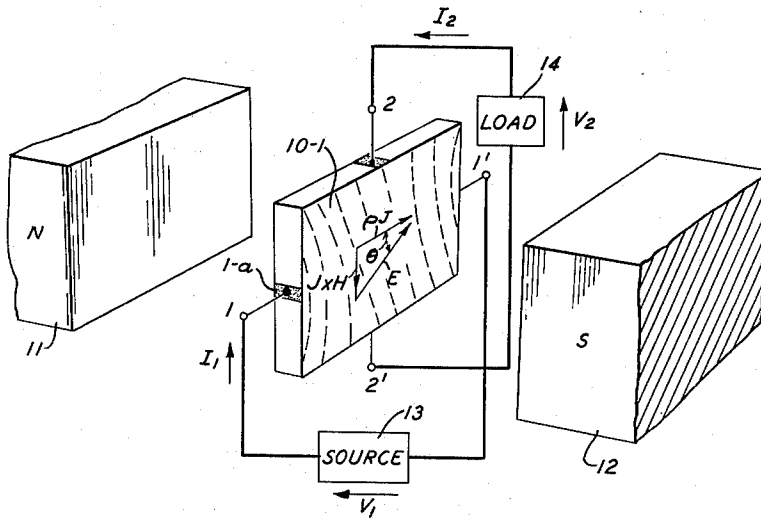


FIG. 2A

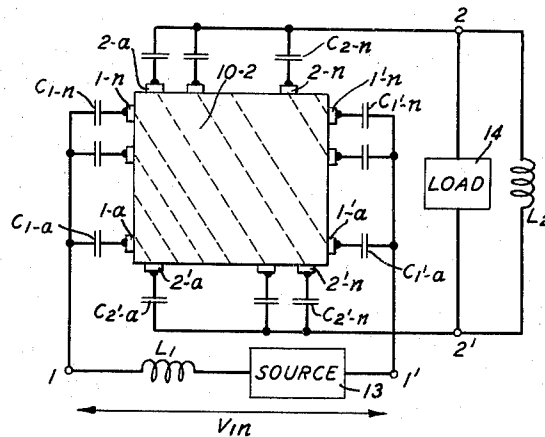
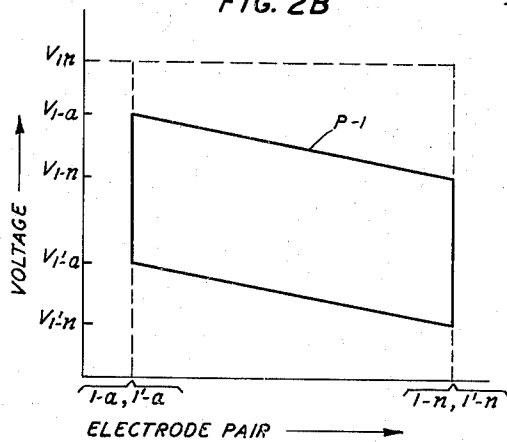


FIG. 2B



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3 Sheets-Sheet 2

FIG. 3B

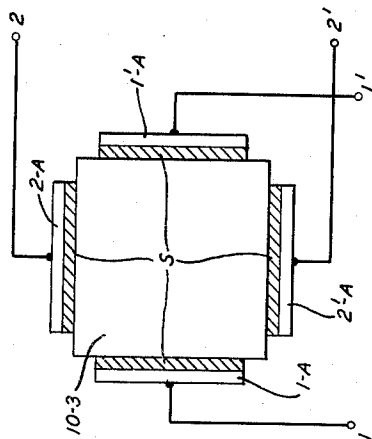


FIG. 5B

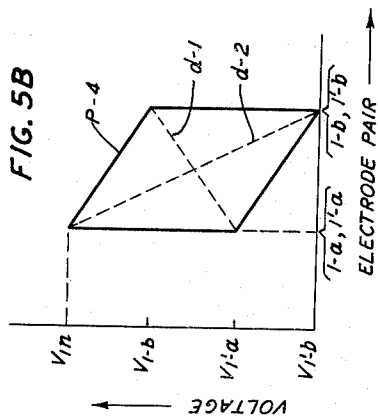


FIG. 3A

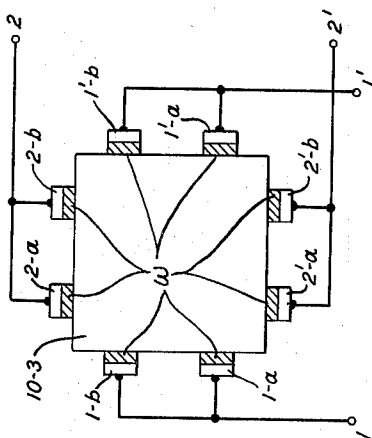
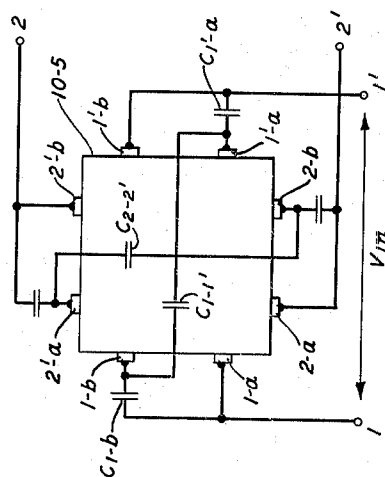


FIG. 5A



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Filed Sept. 26, 1961

3 Sheets-Sheet 3

FIG. 4B

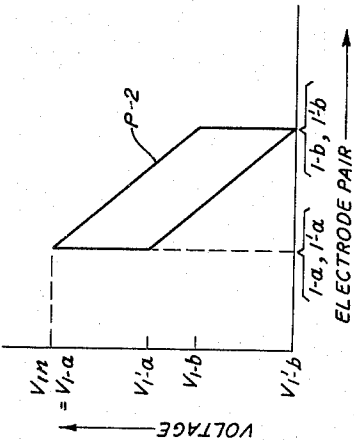


FIG. 4D

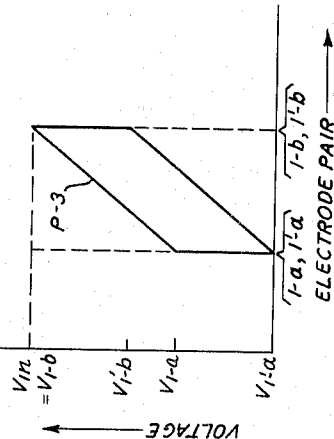


FIG. 4A

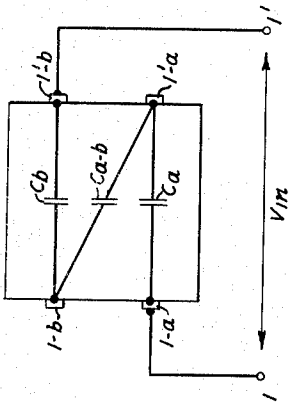
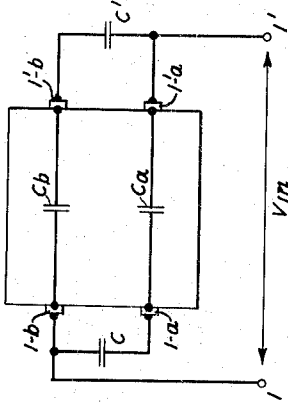


FIG. 4C



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1

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LOW-LOSS HALL-EFFECT DEVICES

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22 Claims. (Cl. 323-94)

This invention relates to Hall-effect devices and, more particularly, to the propagation of signal energy through such devices without substantial energy loss.

According to the Hall effect, a magnetic field is able to reorient an electric field that has been established within a body of material. The effect is particularly notable when the body is semiconductive. As a result, a device incorporating a body of Hall material is able to present disparate transmission characteristics to signals propagated through it in diverse directions. The disparity may be used to advantage in a variety of ways. When it is adapted to produce a transmission null in one direction of propagation, but not in another, the result is a directional device, exemplified by the isolator. Or, when two disparate transmission characteristics are rendered equal in magnitude but opposite in phase, i.e., anti-reciprocal, the result is an impedance converter. Other uses of the special characteristics afforded by Hall materials are discussed by W. J. Grubbs in 38 Bell System Technical Journal, 853 (1959).

In any event, the transmission in at least one direction of propagation should not be adversely affected. Unfortunately, the insertion of a Hall device into a transmission path typically produces a significant reduction in desired signal energy. The resulting insertion loss can often be compensated by amplification, but this detracts from the inherent simplicity of Hall devices. In addition, with an impedance converter, insertion loss causes imperfections in the conversion that are not compensable.

Consequently, it is an object of the invention to reduce undesired insertion loss rather than compensate for it. A related object is to enhance the impedance conversion capability of Hall devices.

At first view it would appear that insertion loss could be reduced by having each terminal affixed to a body of Hall material make conductive contact with it over an appreciable area. However, as the area of contact increases the electric field within the material becomes increasingly distorted. To a limited extent the distortion, and hence the associated increase in insertion loss, can be mitigated changing the configuration of a Hall body. Accordingly, it is an object of the invention to increase the contact area of each terminal without causing appreciable electric field distortion. A related object is to reduce insertion loss without impediment to Hall-device microminiaturization.

As the operating frequency of a Hall device increases, insertion loss becomes of greater consequence and imposes a bound that is far below the theoretical limit given by the dielectric relaxation frequency of a Hall material. Furthermore, corrective techniques that are adequate at low frequencies, such as those involving transformer coupling, are deficient at high frequencies. Thus, it is a further object of the invention to extend the operating frequency range of Hall devices. A related object is to extend the range by the use of corrective techniques which do not possess inherent frequency limitations.

2

The invention accomplishes the foregoing and related objects by capacitively correcting for the electric field distortion that ensues within a body of Hall material when the various terminals of a Hall device make extensive contact with the material. This entails either (1) the capacitive interconnection of terminal subelectrodes, or, (2) the inclusion of dielectric substances between extended electrodes and the Hall body.

With subelectrodes, the capacitive magnitudes of the interconnecting capacitors are so proportioned that electric field distribution sustained at the peripheries of the Hall body is substantially the same as that occurring at the interior, thus mitigating field distortion. Where the capacitive magnitudes are small, the voltages measured across the material are maintained in phase by additional capacitors which cross-couple the subelectrodes.

It is a feature of the invention that the corrective capacitors can be resonated with inductors to match a low-loss Hall device with its terminations.

Other features of the invention will become apparent after the consideration of several illustrative embodiments taken in conjunction with the drawings, in which:

FIG. 1 is a perspective drawing of a Hall device;

FIG. 2A is a circuit diagram incorporating a low-loss gyrator according to the invention;

FIG. 2B is a geometrical diagram explanatory of the invention, as embodied in FIG. 2A;

FIGS. 3A and 3B are schematic diagrams of low-loss gyrators employing distributed capacitance;

FIGS. 4A and 4C are schematic diagrams further illustrating the invention and accompanied by respective explanatory geometrical diagrams of FIGS. 4B and 4D; and

FIGS. 5A and 5B are diagrams relating to a Hall gyrator employing capacitive cross-coupling in accordance with the invention.

Turn now to FIG. 1, illustrating the Hall-effect in a thin semiconductive plate 10-1, typically indium antimonide, that is placed with its principal faces perpendicular to a magnetic field between North and South pole pieces 11 and 12. An input signal from a source 13 is applied to the plate 10-1 at a pair of input terminals 1 and 1' respectively connected to oppositely positioned edge electrodes, of which one such electrode 1-a is visible in FIG. 1.

Because of the electric field force E created by the signal source 13, charged particles move from one electrode to the other. During this movement the particles tend to be deflected by transverse force proportional to the vector cross-product of the magnetic field intensity H and the current density J of the moving charges. The magnetic and electric forces are counterbalanced by a resistive force ρJ measured in terms of the resistivity ρ of the plate and the current density J . The resulting balance of forces is represented by a vector diagram near the center of the face of the plate opposite the south pole piece 12.

Mathematically the balance is stated in Equation 1:

$$\rho J = E + ihJH \quad (1)$$

where h is the Hall coefficient and i symbolizes a rotation of 90 degrees.

Although the magnetic field initially causes a transverse motion of charges, it has been theorized that balancing charges quickly build up near the upper and lower edges of the plate 10-1, so that in the steady state, with no current flow through output terminals 2-2', the current

density vector $\mathbf{J}$ substantially assumes its initial orientation. On the other hand, the electric field $\mathbf{E}$ accrues, with respect to the current density $\mathbf{J}$, a relative rotational displacement given by the Hall angle θ of Equation 2:

$$\theta = \tan^{-1} \frac{hH}{\rho} \quad (2)$$

Because of the electric field displacement, the equipotential regions within the plate 10-1, indicated by dashed lines, become skewed so that opposite points on the upper and lower edges of the plate are no longer at the same potential, as they would be in the absence of an applied magnetic field. If the electrodes of the input and output terminal pairs 1-1' and 2-2' make restricted contact with the plate—to avoid distorting the electric field—the voltage measured across a high magnitude impedance load 14 connected across the output terminals 2 and 2' is proportional to the product of the input voltage V_1 and the magnetic field intensity H , even for a Hall angle θ approaching 90 degrees.

When the electrode configuration is that of FIG. 1, the resulting Hall device is designated a gyrator because the expressions, given in Equation 3, relating its currents and voltages, are analogous to those that apply in the case of a mechanical gyroscope.

$$\begin{aligned} V_1 &= Z_{11}I_1 + Z_{12}I_2 \\ V_2 &= -Z_{12}I_1 + Z_{11}I_2 \end{aligned} \quad (3)$$

where V_1 and V_2 are the input and output voltages, respectively; I_1 and I_2 are the input and output currents, respectively; Z_{11} is the self-impedance and Z_{12} is the transfer impedance.

Since the transfer coefficients Z_{12} and $-Z_{12}$ associated with the input and output currents I_1 and I_2 are of equal magnitude and opposite sign, it is evident that the gyrator functions as an impedance converter to the extent that its self-impedance term Z_{11} becomes negligible. Then the input impedance is approximately Z_{12}^2/Z_{load} .

However, the ordinary circumstance that the self-impedance term Z_{11} is large, i.e., the insertion loss is appreciable, is due in great measure to the restricted contact made with the Hall plate 10-1 by the input and output terminals 1-1' and 2-2'.

On the other hand, the gyrator can be adapted as an isolator by reducing one of the transfer coefficients to zero. One way of doing this is demonstrated in Patent 2,775,658 issued to W. P. Mason et al. But, again, the insertion loss of desired signal energy is significant.

In this context insertion loss L (in bels) is a measure of the reduction in source energy at a load 14 attributable to the existence of an intervening network between the load 14 and the source 13. Stated mathematically in Equation 4, it is the logarithm of the ratio of the load power P in the absence of the intervening network to the load power P' in the presence of the network.

$$L = \log_{10} \frac{P}{P'} \quad (4)$$

For a conventional four-terminal Hall device of the kind shown in FIG. 1, regardless of configuration, this loss cannot be reduced below 7.66 decibels, as demonstrated in 25 Jnl. of Applied Physics, 741 (1954), at page 743.

A reduction of the loss requires an increased contact between each terminal and the plate, without causing electric field distortion. Refer to FIG. 2A where this is accomplished, according to the invention, by subdividing each terminal and including a coupling capacitor in each path that extends from the terminal to a region of the Hall plate 10-2. In particular, the first input terminal 1 is interconnected with distinctive electrodes 1-a through 1-n, conductively affixed to successive regions of the Hall plate, by respective coupling capacitors C_{1-a} through C_{1-n} . A similar arrangement is provided for the remaining terminals 1', 2 and 2'.

To provide a low magnitude input impedance to a voltage source 13 at the input terminals 1-1', the input cir-

cuit coupling capacitors C_{1-a} through C_{1-n} and $C_{1'-a}$ through $C_{1'-n}$ are resonated with a series connected inductor L_1 . At the output terminals 2-2' a high magnitude impedance load 14 is matched with the gyrator through the use of a shunt connected inductor L_2 which is resonated with the output circuit coupling capacitors C_{2-a} through C_{2-n} and $C_{2'-a}$ through $C_{2'-n}$. Of course, in any case the way in which the inductors L_1 and L_2 are connected depends upon the kind of match desired.

Aside from phase considerations, the relative voltages existing among the coupling capacitors of the input circuit can be summarized in a voltage-electrode parallelogram $p-1$ of the kind shown in FIG. 2B. By superposition a similar parallelogram applies for the coupling capacitors in the output circuit.

In FIG. 2B subelectrode pairs are indicated along the axis of abscissas, while various voltage magnitudes are given along the axis of ordinates. For example, the left-hand side of the parallelogram applies to the lowermost subelectrode pair 1-a and 1'-a of FIG. 2A, so that the magnitude of the voltage developed across the first coupling capacitor C_{1-a} is given by the ordinate distance between the marker for the voltage V_{in} developed across the input terminal 1-1' and the marker for the voltage V_{1-a} developed at the lower left-hand electrode 1-a. Similar considerations apply for the other capacitors. In each case, the total capacitance in the path of oppositely positioned subelectrodes is the same, with relative magnitudes being selected to fit the requirements indicated by the parallelogram $p-1$. It follows from the specific configuration of the parallelogram $p-1$ in FIG. 2B that the capacitive magnitude of the first capacitor C_{1-a} is approximately double that of the last capacitor C_{1-n} , i.e., $|C_{1-a}| \cong 2|C_{1-n}|$.

Regardless of magnitude, the coupling capacitors required in FIG. 2A can be provided without impediment to microminiaturization. This is accomplished for the gyrator of FIG. 3A, having two subelectrodes a and b per terminal, by sandwiching wafers w of dielectric material between the subelectrodes a and b and the Hall plate 10-3. For coupling capacitances that are of sufficiently small magnitude, the wafers w are of uniform thickness.

As the number of subelectrodes increases the insertion loss decreases. Then it is advantageous to continuously join the wafers and subelectrodes of each term. The result is indicated in FIG. 3B, for which respective sheets S of dielectric material are included between extended terminal electrodes 1-A, 1'-A, 2-A, and 2'-A and the Hall plate 10-3. When the coupling capacitances are small, the sheets S are of uniform thickness; otherwise, they are tapered.

The configuration presented in FIG. 2A typifies but one way of capacitively interconnecting subelectrodes to maintain an appropriate electric field distribution at the peripheries of a Hall plate.

Two other ways are indicated, for input subelectrodes only, of which there are two subelectrodes a and b per terminal, in FIGS. 4A and 4C, respectively. Coupling capacitors C_a and C_b , interconnecting oppositely positioned subelectrodes, are supplemented by a diagonal coupling capacitor C_{a-b} in FIG. 4A and by two intercoupling capacitors C and C' in FIG. 4C. The relative voltages existing among the coupling capacitors in FIGS. 4A and 4C are obtainable from respective voltage-electrode parallelograms $p-2$ and $p-3$ of FIGS. 4B and 4D.

With the foregoing embodiments, presented in FIGS. 2A, 3A, 3B, 3C and 4A, electric field distortion is minimized when the capacitive magnitudes of the coupling capacitors are small. But, under that circumstance, the inductances used for matching purposes, such as those provided by the tuning inductors L_1 and L_2 of FIG. 2A, must be of correspondingly large magnitudes at a prescribed frequency. The result is narrow-band operation about that frequency.

For wide-band operation the capacitive magnitudes of the coupling capacitors are made appreciable. Then, how-

ever, the voltages measured across a Hall plate between diagonally positioned subelectrodes tend to be out-of-phase, evidencing electric field distortion. This difficulty is remedied by the use of cross-coupling capacitors—which are needed only when the capacitive magnitudes of the coupling capacitors are large.

In the two-subelectrode per terminal Hall device of FIG. 5A, based upon the prototype of FIG. 2A with one coupling capacitor omitted at each terminal, only two cross-coupling capacitors $C_{1-1'}$ and $C_{2-2'}$, are required, although generally there is one cross-coupling capacitor per diagonal path.

Associated with the input circuit of FIG. 5A is a voltage-electrode parallelogram $p-4$ given in FIG. 5B, similar to that of FIG. 2B, as modified to account for the omission of a subelectrode coupling capacitor at each terminal. The diagonals $d-1$ and $d-2$ of the parallelogram indicate the subelectrode pairs whose measured voltages are brought into phase by the cross-coupling capacitor $C_{1-1'}$ of the input circuit.

If the input circuit cross-coupling capacitor $C_{1-1'}$ is of a substantial capacitive magnitude, considerably in excess of the resistive magnitude between the cross-coupled subelectrodes $1-b$ and $1'-a$, the voltage measured between the subelectrodes will be substantially an in-phase with, and a fractional portion of, the input voltage V_{in} appearing at the other diagonally positioned subelectrodes $1-a$ and $1'-b$. For the specific parallelogram of FIG. 4B all the capacitors have like magnitude capacitances. Additional cross-coupling capacitors are used as the number of subelectrodes per terminal increases beyond two.

Other correctional techniques for reducing the insertion losses of Hall devices will occur to those skilled in the art. It will also be appreciated that a Hall device corrected according to the invention may be of arbitrary configuration and employment.

What is claimed is:

1. Low-loss Hall-effect apparatus comprising a multi-terminal body of Hall-effect material, each terminal making contact with said body over a plurality of regions, and, for each terminal, capacitive means interconnecting all of said regions.

2. Apparatus as defined in claim 1 wherein said capacitive means comprises a body of dielectric material.

3. Apparatus as defined in claim 1 further including capacitive means interconnecting a region contacting one terminal with a region contacting another terminal.

4. Apparatus as defined in claim 1 further including means for resonating said capacitive means.

5. Low-loss Hall-effect apparatus comprising a multi-terminal body of Hall-effect material, at least one terminal making contact with said body over a plurality of regions, the other terminals making contact with said body over at least one region, and capacitive means interconnecting said regions.

6. Low-loss Hall-effect apparatus comprising a body of Hall-effect material, a plurality of terminals, conduction means extending from each terminal and encompassing a set of regions on said body, and capacitive means included in said conduction means.

7. Apparatus as defined in claim 6 wherein said conduction means has a branch conduction means for each region of said set and said capacitive means is included in one of the branch conduction means.

8. Apparatus as defined in claim 7 further including capacitive means interconnecting a branch conduction means of one terminal with a branch conduction means of another terminal.

9. Apparatus as defined in claim 6 wherein the regions of said set are adjoining and said capacitive means comprises a body of dielectric material that is affixed to said first named body and is coextensive with the adjoining regions.

10. Low-loss Hall-effect apparatus comprising a body of Hall-effect material, means connected to said body over

an extensive region thereof for establishing an electric field therein, magnetic field means for reorienting said electric field according to the Hall effect, whereby the re-oriented electric field is distorted in the vicinity of said extensive region, and capacitive means included in the path of said establishing means for countering the distortion of said reoriented field, thereby to reduce the loss of energy within said body.

11. Apparatus as defined in claim 10 wherein said capacitive means comprises capacitors interconnecting subregions of said extensive region with each other.

12. Apparatus for reducing the insertion losses of signals propagated through a semiconductive Hall-effect plate, which comprises at least three terminals affixed at the edges of the plate, at least one of said terminals contacting an edge of said plate at a plurality of distinctive points, means for applying an input signal to two of said terminals, means for extracting an output signal from two of said terminals, means for applying a magnetic field with a component perpendicular to the principal faces of said plate, whereby a portion of said input signal is diverted to the output terminals and undesired parasitic currents flow in the vicinity of said distinctive points of contact, and means for capacitively interconnecting said points of contact, thereby to curtail the flow of said parasitic currents.

13. Apparatus comprising a body of Hall-effect material in which there is generated an electric field, a plurality of terminals making extensive contact with said body in order to reduce insertion losses and thereby distorting its electric field, and, between each terminal and said body, means for reducing the distortion of said electric field.

14. Apparatus comprising a body of Hall-effect material having distinctive regions, a plurality of terminals for said body, a plurality of paths jointly interconnecting one of said terminals with one of said regions, capacitive means included in one of said paths, and means connecting the others of said terminals to other regions of said body.

15. Apparatus comprising a body of Hall-effect material, a pair of input terminals, and, for each of said input terminals, a plurality of paths extending to said body and capacitive means included in one of said paths.

16. A Hall-effect device comprising a thin semiconductive plate having a plurality of edges, a separate group of subelectrodes connected to each of selected edges, a distinctive terminal connected to each group of said subelectrodes, and capacitive means connected to selected terminals.

17. Apparatus as defined in claim 16 wherein said capacitive means comprises a plurality of dielectric layers separately connecting selected ones of said subelectrodes to said edges.

18. Apparatus as defined in claim 16 wherein said capacitive means comprises a plurality of capacitors separately interconnecting one subelectrode of each group with the terminal associated therewith.

19. Apparatus as defined in claim 18 wherein the subelectrodes of two groups thereof are oppositely positioned in pairs along said edges, and the capacitors are proportioned to produce the same total capacitance for each subelectrode pair.

20. Apparatus as defined in claim 19 wherein said capacitors are further proportioned to distribute said total capacitance between the subelectrodes of each successive pair thereof as a linear function of position.

21. Apparatus as defined in claim 18 further including a capacitor interconnecting a subelectrode of one group with a subelectrode of another group.

7

22. Apparatus which comprises
a body of Hall-effect material in which there is generated an electric field,
a plurality of large contact areas around the periphery of said Hall-effect material, said plurality of large contact areas distorting said electric field while reducing the loss of energy in said Hall-effect material, capacitive means attached to said plurality of large contact areas, said capacitive means being proportioned to eliminate said distortion of said electric field, and conductive means connected to said capacitive means.

5
10

8

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