

April 21, 1970

J. A. COPELAND III

3,508,169

APPARATUS INCLUDING LSA OSCILLATOR CIRCUITS

Filed June 20, 1967

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FIG. 1

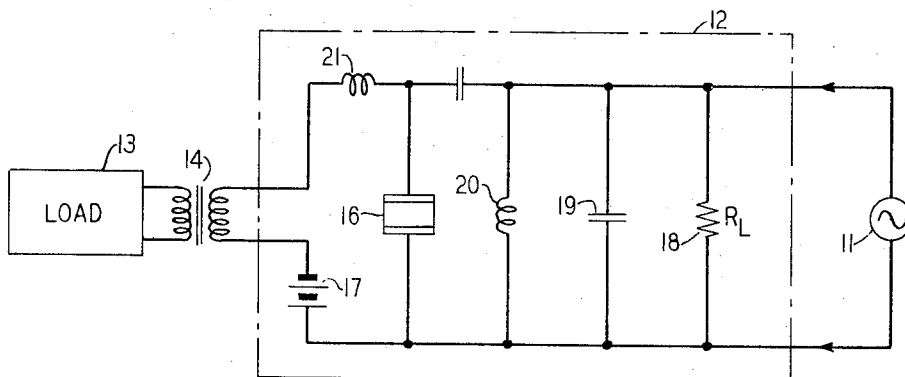


FIG. 4

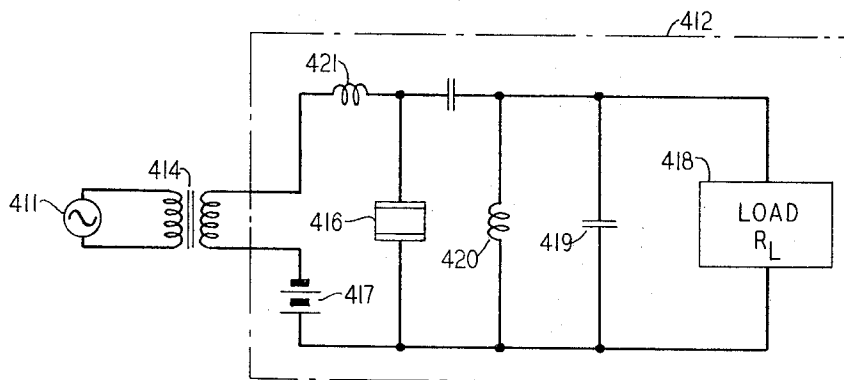
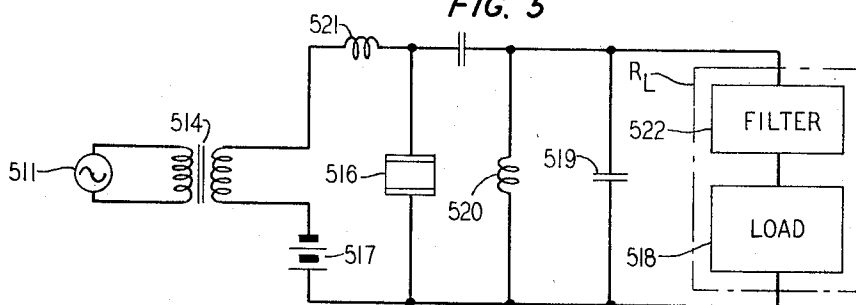


FIG. 5



INVENTOR
J. A. COPELAND III
BY
Robert B. Anderson
ATTORNEY

April 21, 1970

J. A. COPELAND III

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FIG. 2A

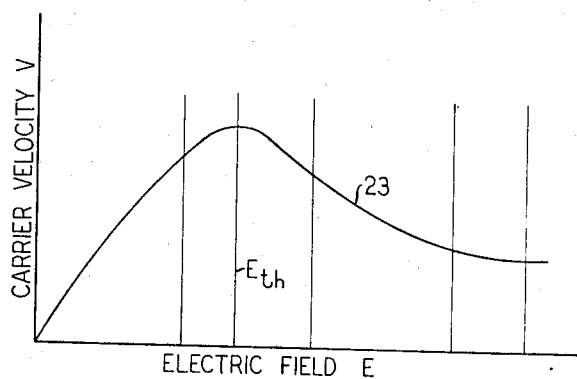


FIG. 2B

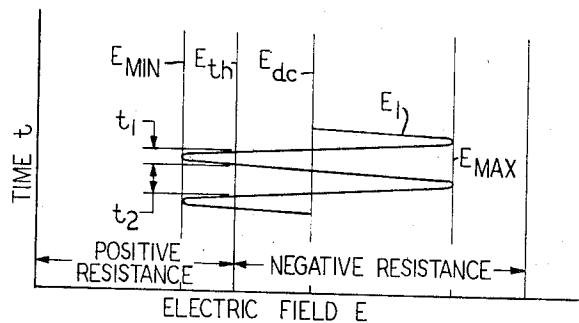


FIG. 2C

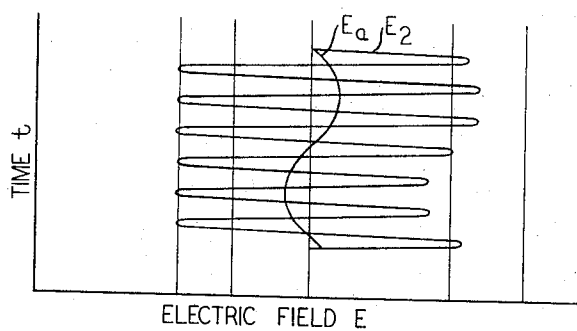
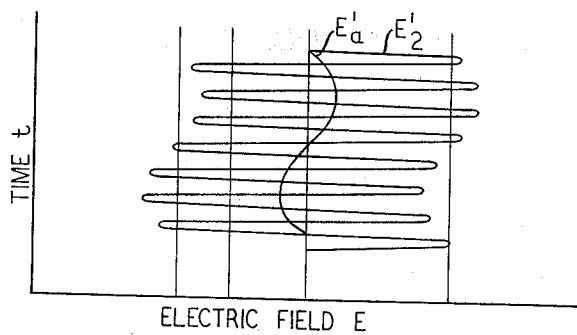


FIG. 2D



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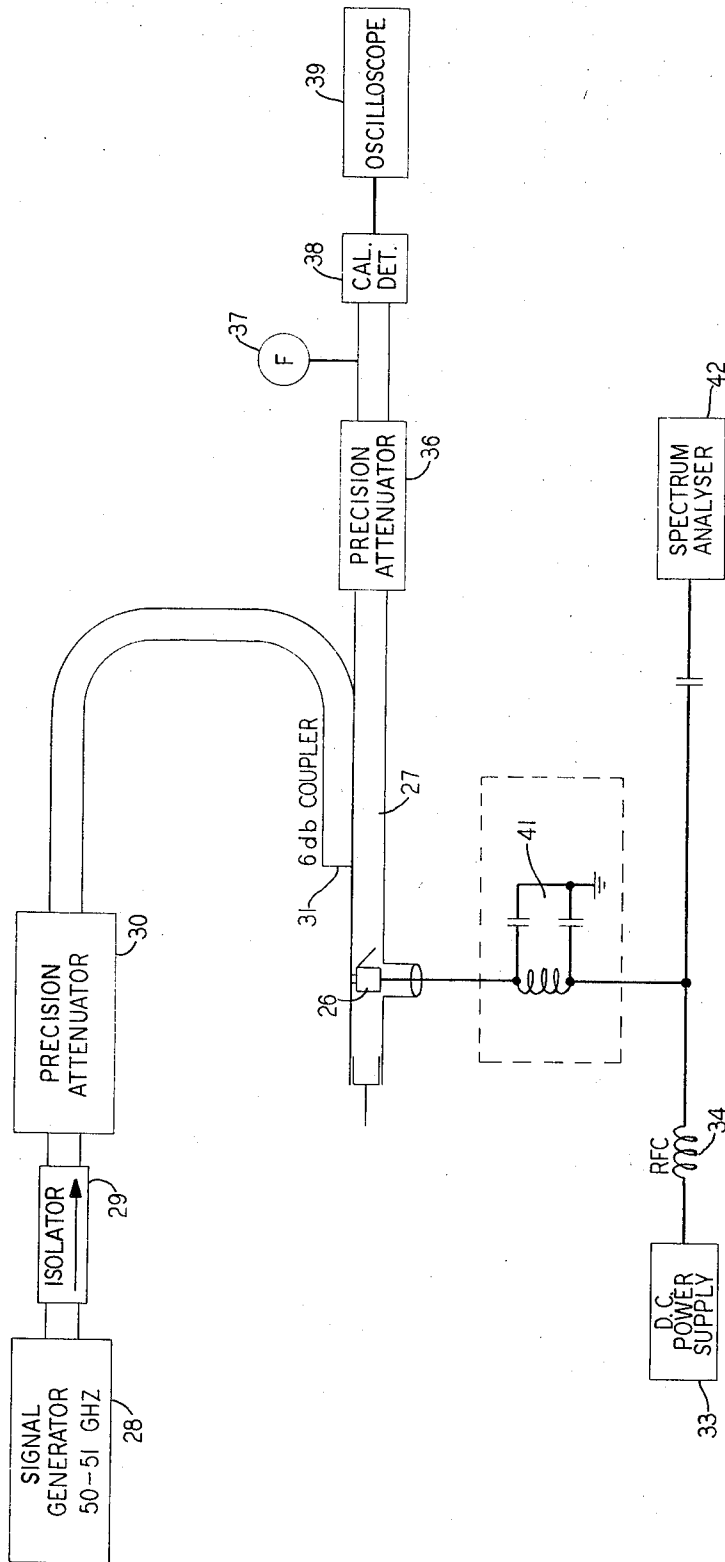
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FIG. 3



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APPARATUS INCLUDING LSA OSCILLATOR CIRCUITS

John A. Copeland III, North Plainfield, N.J., assignor to Bell Telephone Laboratories, Incorporated, Murray Hill and Berkeley Heights, N.J., a corporation of New York
Filed June 20, 1967, Ser. No. 647,419

Int. Cl. H03c 1/14; H03f 3/10; H02m 5/20

U.S. Cl. 332—52

13 Claims

ABSTRACT OF THE DISCLOSURE

In one embodiment, an input signal is applied to an LSA oscillator circuit where it mixes with the oscillatory frequency f_{LSA} to give a difference frequency f_a that is amplified. In another embodiment, a signal of frequency f_a applied to an LSA oscillator modulates the oscillatory output frequency. In another embodiment, an input frequency f_a mixes with the oscillatory frequency to give an amplified sum frequency. In all the above embodiments, f_a conforms to the relationship

$$f_a \lesssim \frac{f_{LSA}}{Q}$$

where Q is the quality factor of the oscillator resonance circuit.

BACKGROUND OF THE INVENTION

The structure and operation of two-valley devices, also known as bulk-effect devices, are described in detail in a series of papers in the January 1966 issue of the IEEE Transactions on Electron Devices, vol. ED-13, No. 1. As is set forth in these papers, a negative resistance can be obtained from a bulk semiconductor wafer of substantially homogeneous constituency having two energy band minima within the conduction band which are separated by only a small energy difference. By establishing a suitably high electric field across opposite ohmic contacts of the semiconductive wafer, oscillations can be induced which result from the formation of discrete regions of high electric field intensity and corresponding space-charge accumulation, called domains, that travel from the negative to the positive contact at approximately the carrier drift velocity. A characteristic of the two-valley semiconductor material is that it presents a negative differential resistance to internal currents in regions of high electric field intensity. Hence, the electric field intensity of the domain grows as it travels toward the positive electrode.

Oscillators which operate according to this principle were first described in the paper "Instabilities of Current in III-V Semiconductors," by J. B. Gunn, IBM Journal, April 1964, and are now generally known as Gunn oscillators. The domains are formed successively which results in an oscillation frequency that is approximately equal to the carrier drift velocity divided by the wafer length. Since the oscillation frequency is a function of length, Gunn oscillators are inherently frequency and power limited; as the sample length is reduced to give higher frequency, the attainable power decreases.

The copending patent application of J. A. Copeland III, Ser. No. 564,081, filed July 11, 1966, and assigned to Bell Telephone Laboratories, Incorporated, and the paper by J. A. Copeland III, "A New Mode of Operation for Bulk Negative Resistance Oscillators," Proceedings of the IEEE, October 1966, pp. 1479-1480, describe how a new mode of oscillation, called the LSA mode (for Limited Space-charge Accumulation), can be induced in Limited Spacecharge Accumulation), can be induced in two-valley devices. This new mode of oscillation is not dependent on the formation of traveling domains, its

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frequency is not dependent on wafer length, and as a result, the oscillator does not have the frequency and power limitations of the Gunn oscillator. The LSA mode oscillator includes a two-valley semiconductor diode, a resonant circuit, and a load, the various parameters of which are adjusted such that the electric field intensity within the diode alternates between a high value at which negative resistance occurs, and a lower value at which the diode displays a positive resistance. By appropriately adjusting the duration of electric field excursions into the positive and negative regions of the diode, one can prevent the formation of the traveling domains responsible for Gunn-mode oscillation, while still obtaining the net negative resistance required for sustained oscillations.

The LSA mode oscillator is a particularly significant invention because it generates, at usefully high power levels, higher frequencies than other solid state sources and does not have the various drawbacks such as instability, high noise level, bulk, and power consumption that characterize microwave tube oscillators such as the klystron. It therefore offers the possibility of practical communication systems at higher microwave frequencies than those presently used. However, certain presently used microwave components such as modulators and crystal detectors are incapable of operating efficiently or of operating at all at some of these frequencies, particularly frequencies in the millimeter wavelength region.

SUMMARY OF THE INVENTION

I have found that while the LSA oscillator is oscillating, it presents a negative resistance to voltages applied across the diode which have a sufficiently low frequency to permit oscillatory energy in the resonant circuit to change in amplitude during each cycle of the applied voltage. This condition implies a limiting relationship of the applied frequency f_a , the LSA oscillatory frequency f_{LSA} , and the quality factor Q of the resonant circuit, which is a measure of the circuit energy storage capability. This relationship can be approximated as,

$$f_a < \frac{f_{LSA}}{Q} \quad (1)$$

Hence, if a frequency f_a is applied to the diode, it will be amplified by the diode negative resistance.

In another embodiment in which the LSA oscillatory circuit is used as a local oscillator, mixer, and amplifier, an input signal at a frequency equal to $f_{LSA} \pm f_a$ is applied to the circuit. It can be shown that the diode is inherently nonlinear, which results in mixing of the input and oscillatory frequencies to give a difference frequency f_a . With the difference frequency conforming to relationship (1), it is amplified by the diode negative resistance.

In another embodiment, a varying signal having a frequency f_a is used to amplitude modulate the LSA oscillation frequency. Because the frequency f_a is low enough to permit amplitude adjustment each cycle by the oscillation frequency, it is effective in modulating the oscillation frequency, and further, the modulating frequency is amplified due to the diode negative resistance.

In still another embodiment, the frequency f_a is applied and the oscillation output is filtered to retrieve the sum frequency $f_a + f_{LSA}$. This embodiment is an efficient local oscillator, amplifier, and up-converter mixer.

DRAWING

These and other objects, features and advantages of the invention will be better understood from a consideration of the following detailed description taken in conjunction with the accompanying drawing in which:

FIG. 1 is a schematic drawing of an oscillator, mixer, and amplifier in accordance with one embodiment of the invention;

FIG. 2A is a graph of electron velocity v versus electric field E in the diode of the circuit of FIG. 1;

FIGS. 2B through 2D are graphs of time t versus electric field E in the diode of the circuit of FIG. 1 under various conditions of operation;

FIG. 3 is a schematic diagram of a microwave frequency embodiment of the circuit of FIG. 1;

FIG. 4 is a schematic diagram of another embodiment of the invention; and

FIG. 5 is a schematic diagram of still another embodiment of the invention.

DETAILED DESCRIPTION

Referring now to FIG. 1 there is shown schematically an oscillator, mixer and amplifier circuit comprising a signal source 11, an LSA oscillator 12, and a load 13 connected to the oscillator by a transformer 14. The LSA oscillator circuit comprises a semiconductor diode 16 connected to a D-C voltage source 17, a load resistance 18, and a resonant tank circuit comprising a capacitance 19 and an inductance 20. The diode 16 comprises a sample of two-valley semiconductor material included between substantially ohmic contacts. The sample may be of n-type gallium arsenide of substantially uniform constituency which is doped in a manner known in the art to give a negative resistance characteristic as shown by curve 23 of FIG. 2A. For purposes of this application, the term two-valley device shall mean any semiconductor device having a carrier velocity versus electric field characteristic of the general type shown in FIG. 2A. For n-type materials, the carrier velocity refers to electron velocity and for p-type materials it refers to hole velocity.

If the A-C source 11 were not connected to the circuit of FIG. 1, the LSA oscillator 12 would operate in substantially the manner described in the aforementioned Copeland application to generate a high frequency electric field E_1 in the diode having a relationship to the electric field E_{dc} applied by voltage source 17 as depicted in FIG. 2B. As shown in FIGS. 2A and 2B, the bias voltage across the diode E_{dc} is higher than the threshold voltage E_{th} at which negative resistance within the diode occurs. During the time interval t_1 of each cycle of E_1 , the voltage in the diode extends below the threshold voltage E_{th} into the positive resistance of the diode, while during the remaining portion of the cycle t_2 it extends into the negative resistance region above E_{th} . The frequency E_1 is determined by the oscillator resonant circuit, while the amplitude is a function of the load resistance R_L of the circuit.

In spite of the fact that the electric field E_1 extends into the positive resistance region, the gain of the device will exceed its attenuation if the following relationship is satisfied,

$$\frac{1}{t_1 + t_2} \int^{(t_1 + t_2)} E_1 v dt < E_{dc} v_a \quad (2)$$

where the integral is taken over one cycle, E_1 is the electric field, v is the carrier velocity, and v_a is the average carrier drift velocity in the sample during oscillation. As pointed out in the Copeland application, traveling domains in the sample are prevented by making the time interval t_2 small enough so that substantial space-charge accumulation cannot occur during that time interval, and by making t_1 long enough to attenuate space-charge accumulation to prevent it from growing with succeeding cycles. To meet these requirements the following relations should also be satisfied,

$$\frac{ne}{\epsilon} \int^{(t_2)} |\mu| dt < 10 \quad (3)$$

$$\frac{ne}{\epsilon} \int^{(t_1)} |\mu| dt > \frac{ne}{\epsilon} \int^{(t_2)} |\mu| dt \quad (4)$$

where $\int^{(t_2)}$ is the integral taken over the time period t_2 , ϵ is the permittivity of the sample, μ is the differential mobility of the sample dv/dE_1 , e is the charge on a majority carrier, and $\int^{(t_1)}$ is the integral taken over time period t_1 .

In order to give the oscillating field E_1 sufficient amplitude to extend into the positive resistance region and to rise sharply into the negative resistance region, the circuit should be "lightly loaded"; i.e., the effective parallel load resistance should be fairly high. For a gallium arsenide diode, it is recommended in the Copeland application that the load resistance conform to the relationship,

$$R_L > \frac{l}{n_0 |\mu_2| e A} \quad (5)$$

where l is the length of the sample, n_0 is the doping level or average carrier concentration of the sample, A is the area of the sample in a plane transverse to the drift current, and μ_2 is the average mobility in a negative resistance region which is given by,

$$|\mu_2| = \frac{1}{t_2} \int^{(t_2)} |\mu| dt \quad (6)$$

With fulfillment of the above conditions, oscillator circuit 12 operates in the LSA mode without the formation of traveling domains within the diode 16. The application of J. A. Copeland III, Ser. No. 612,598, filed Jan. 30, 1967, and assigned to Bell Telephone Laboratories, Incorporated points out that oscillations may be initiated either by transient effects or through the application of a burst of R-F energy.

FIG. 2C shows the effect of the applied signal from signal source 11 of FIG. 1 on the oscillation field E_{LSA} of the LSA oscillator. Assume first that the signal has a frequency f_a giving rise to an electric field component E_a superimposed on the D-C bias as shown in FIG. 2C. As is known, stable steady-state operation of a negative resistance oscillator requires that the magnitude of the negative resistance be equal to the magnitude of the load resistance. If the frequency f_a of the applied field E_a is sufficiently low with respect to the ratio of the frequency f_{LSA} of E_{LSA} to the quality factor of the resonant circuit of the oscillator, the amplitude of E_{LSA} will change during each cycle to reach the steady-state condition at which the negative resistance equals the load resistance. This condition is depicted in FIG. 2C in which it can be seen that the amplitude of E_{LSA} does change with the fluctuations of E_a . Since the circuit is stable, and E_a is in the negative resistance region of the diode, E_a will become amplified.

If, on the other hand, the frequency of E_a is so high with respect to the oscillation frequency and the charge-storage capability of the resonant circuit that the oscillation frequency does not have time to reach a steady-state condition during each cycle, then the total negative resistance of the diode will not equal the load resistance and the applied field E_a will not experience a net negative resistance. This condition is depicted in FIG. 2D in which the applied field E'_a has such a high frequency with respect to the oscillation frequency of E_{LSA} that the amplitude of E'_{LSA} cannot change with changes of E'_a . As a result, E'_{LSA} extends into a region of low positive resistance and the component E'_a is not amplified.

The condition for amplification of the applied field E_a can be generalized as follows: if the frequency f_a of the applied field E_a is sufficiently low to permit LSA oscillatory mode energy in the resonant circuit to change in amplitude during each of its cycles in accordance with voltage changes of E_a , then E_a will be amplified. This in turn requires that the frequency f_{LSA} of the oscillatory mode be sufficiently high, and the energy-storage quality factor of the resonant circuit be sufficiently low, with respect to the applied frequency f_a . These requirements

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for amplification of the frequency f_a may be approximated by the relation,

$$f_a \lesssim \frac{f_{LSA}}{Q} \quad (7)$$

where Q is the quality factor of the resonant circuit, which in turn is a measure of the energy-storage capability with respect to frequency of the circuit.

Presently known LSA mode oscillators using two-valley semiconductor diodes require a resonant circuit Q which is greater than at least 5. From relationship (7) this limits the frequency f_a that can be amplified, and as a practical matter, f_a must be much smaller than the oscillation frequency f_{LSA} . For this reason, the circuit of FIG. 1 is more promising as a local oscillator, mixer, and amplifier circuit, than as a carrier frequency amplifier circuit.

Assume that the frequency of the signal from source 11 is equal to $f_{LSA} \pm f_a$. Since two-valley semiconductor diodes are non-linear, the applied signal will mix with the LSA frequency to give a difference frequency component f_a . If the difference frequency f_a conforms with relationship (7), it will be amplified as described before. Transformer 14 and R-F choke 21 of FIG. 1 may be designed as a low-pass filter to pass only the amplified frequency f_a to the load 13. Hence, the circuit of FIG. 1 may be useful in communications systems for down-converting and amplifying an incoming carrier wave having a higher frequency than could be detected by conventional crystal detectors.

FIG. 3 shows a schematic diagram of a microwave version of the circuit of FIG. 1 in which the two-valley semiconductor diode 26 is mounted in a waveguide 27, part of which constitutes the oscillator resonant circuit. An input signal from a source 28 is directed through an isolator 29, a precision attenuator 30 and a 6 db coupler 31 to the waveguide 27. The diode 26 is biased by a D-C power supply 33 which is directed to the diode by way of a radio frequency choke 34. The LSA oscillator circuit includes a precision attenuator 36, a frequency meter 37, a calibrated detector 38, and an oscilloscope 39. The output circuit of the device includes a low-pass filter 41 and a spectrum analyzer 42.

The circuit shown in FIG. 3 has been built and tested to demonstrate mixing and amplification of the lower sideband frequency. The LSA oscillator circuit was designed to operate at a frequency f_{LSA} of 50 gigahertz with -10 dbm. output power. The signal of 50 to 51 gigahertz mixed with the LSA frequency to give outputs detected by the spectrum analyzer 42 at 30 megahertz and 180 megahertz with a gain of about 16 db. The Q of the oscillator resonant circuit was computed as being 100. The overall noise figure was found to be about 20 db.

Referring to FIG. 2C, since the amplitude of the LSA electric field E_2 varies with the applied field E_a , it is clear that E_a could be used to amplitude modulate the LSA oscillation frequency. FIG. 4 shows an LSA oscillator circuit which has been modified to give amplitude modulation of the output in accordance with this principle. The last two digits of each of the reference numerals of the circuit of FIG. 4 designate components which have functions analogous to components of FIG. 1 having the same two digit reference numeral. The components within the dotted line 412 constitute an LSA oscillator circuit. A modulating signal from source 411 having a frequency f_a that corresponds to relationship (7) is applied across the diode 416. This frequency modulates the amplitude of the oscillatory output as depicted in FIG. 2C, and this usable output is delivered to the load 418 having a load resistance R_L which corresponds to the load resistance R_L of FIG. 1. It is, of course, contemplated that amplitude variations of the modulating signal constitute information to be transmitted.

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Since the diode 416 is nonlinear, the applied frequency f_a mixes with the oscillating frequency f_{LSA} to give an upper sideband frequency $f_a + f_{LSA}$. If this frequency is derived at the load to the exclusion of other component frequencies, the circuit operates as a frequency up-converter, as shown in FIG. 5. In FIG. 5, a filter 522 is included in the output circuit of the LSA oscillator to filter out all frequencies except the sum frequency. With frequency f_a being delivered by source 511, the frequency $f_a + f_{LSA}$ is delivered to the load 518, and the circuit operates as a frequency up-converter. If the frequency f_a complies with relationship (7) the sum frequency is amplified, and the circuit constitutes an up-converter and an amplifier. Alternatively, the frequency $f_{LSA} - f_a$, which may also be considered to be sum frequency, may be derived.

In summary, my invention is based on the discovery that an LSA oscillator will present a negative resistance to a limited band of applied frequencies f_a which are sufficiently low to permit LSA oscillatory mode energy in a resonant circuit to change amplitude each cycle. As a result, the LSA oscillator circuit can be operated as a direct amplifier of frequency f_a or as an amplitude modulator circuit. Because the two-valley semiconductor diode is nonlinear, the circuit can also be operated as a combination local oscillator, mixer, and amplifier for generating and amplifying either upper or lower sideband frequencies. The various embodiments shown and described are intended, however, to be illustrative of the principles of the invention. Various other arrangements may be made by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In a circuit of the type comprising a two-valley semiconductor device connected to a D-C voltage source, a load resistance, and a resonant circuit having a characteristic frequency and a quality factor Q , the parameters of the semiconductor device, voltage source, load resistance, and resonant circuit being arranged to give oscillation in the device in the LSA mode at a frequency f_{LSA} , the improvement comprising:

means for applying to said semiconductor device alternating-current electrical energy at a frequency f_a which is sufficiently low to permit LSA oscillatory mode energy in said resonant circuit to change in amplitude each cycle in accordance with voltage changes of said applied energy, whereby the frequency f_a is amplified.

2. The improvement of claim 1 wherein:

the frequency f_a of said applied energy substantially conforms to the relationship

$$f_a \lesssim \frac{f_{LSA}}{Q}$$

3. The improvement of claim 1 wherein:

the energy applying means comprises means for applying input energy at a frequency $f_{LSA} \pm f_a$, whereby the input and LSA oscillation frequencies mix to generate and apply the frequency f_a .

4. The improvement of claim 1 wherein:

the energy applying means comprises a source of varying signals, whereby the oscillatory energy across the load resistance is amplitude modulated by said varying signals.

5. The improvement of claim 1 wherein:

the frequency f_a mixes with the oscillatory frequency to give a frequency $f_a + f_{LSA}$; and further comprising means for deriving the frequency $f_a + f_{LSA}$ comprising means for filtering out the frequency f_a and f_{LSA} , whereby the circuit constitutes an oscillator, up-converter and amplifier.

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6. The improvement of claim 4 wherein:
the frequency f_a substantially conforms to the relation,

$$f_a \lesssim \frac{f_{LSA}}{Q}$$

7. The improvement of claim 5 wherein:
the frequency f_a substantially conforms to the relation,

$$f_a \lesssim \frac{f_{LSA}}{Q}$$

8. In combination:

means for converting an input signal of frequency $f_{LSA} \pm f_a$ to a lower frequency f_a and for amplifying frequency f_a comprising a two-valley semiconductor device connected to a D-C voltage source, a load resistance, and a resonant circuit having a characteristic frequency and a quality factor Q , the parameters of the semiconductor, voltage source, load resistance, and resonant circuit being arranged to give oscillation in the device in the LSA oscillatory mode at a frequency f_{LSA} , and means for applying said input signal frequency $f_{LSA} \pm f_a$ to said semiconductor device, whereby said input signal and LSA oscillatory mode frequencies mix to generate a difference frequency component f_a ;

the frequency f_a being sufficiently low to permit LSA oscillatory mode energy in said resonant circuit to change in amplitude each cycle in accordance with frequency f_a , whereby the frequency f_a is amplified.

9. The combination of claim 8 wherein:
the frequency f_a substantially conforms to the relationship

$$f_a \lesssim \frac{f_{LSA}}{Q}$$

10. The combination of claim 9 wherein:

the D-C voltage source, the resonant circuit, and the load resistance constitute means for producing within the two-valley semiconductor device an electric field that oscillates at frequency f_{LSA} between positive and negative differential resistance regions, the time interval of each cycle of oscillation during which the electric field is in the negative resistance region being sufficiently large to give a net gain over the entire cycle, and the time interval during which the electric field is in the positive resistance region being sufficiently large to preclude the formation of traveling domains within the device.

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11. In combination:

means for generating an oscillatory output frequency f_{LSA} and for amplitude modulating said output frequency comprising a two-valley semiconductor device connected to a D-C voltage source, a load, and a resonant circuit having a characteristic frequency equal to f_{LSA} and a quality factor Q , the parameters of the semiconductor, voltage source, load, and resonant circuit being arranged to give oscillation in the device in the LSA oscillatory mode at the frequency f_{LSA} , and means for applying a modulating signal of frequency f_a to said semiconductor device; the frequency f_a being sufficiently low to permit LSA oscillatory mode energy in said resonant circuit to change in amplitude each cycle in accordance with the frequency f_a , whereby the output oscillatory energy delivered to the load is amplitude modulated.

12. The combination of claim 11 wherein:

the frequency f_a substantially corresponds to the relationship

$$f_a \lesssim \frac{f_{LSA}}{Q}$$

13. In combination:

means for amplifying and converting an input signal of frequency f_a to a higher frequency comprising a two-valley semiconductor device connected to a D-C voltage source, a load resistance, and a resonant circuit having a characteristic frequency and a quality factor Q , the parameters of the semiconductor, voltage source, load resistance, and resonant circuit being arranged to give oscillation in the device in the LSA oscillatory mode at a frequency f_{LSA} , and means for applying said input signal frequency to said semiconductor device, whereby said input signal and LSA oscillatory mode frequencies mix to generate a sum frequency component;

the frequency f_a being sufficiently low to permit LSA oscillatory mode energy in said resonant circuit to change in amplitude each cycle in accordance with frequency f_a .

No references cited.

45 ROY LAKE, Primary Examiner

D. R. HOSTETTER, Assistant Examiner

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50 307—88.3; 330—5; 325—443, 445, 438, 485, 491