DISTRIBUTED AMPLIFIERS

DEFINITION AND STRUCTURE

The objective of this article is to present various aspects of distributed amplifiers. Distributed amplifiers are, by definition, electronic amplifiers consisting of distributed circuit parameters. Distributed circuit is a transmission line circuit, and the physical length is comparable to operating wavelength. However, in practice, an amplifier system consists of a number of discrete amplifiers associated with distributed parameter circuits, often termed the distributed amplifier. The latter amplifier is actually a pseudo-distributed amplifier.

In practice, the distributed parameter circuit often takes the form of a transmission line. The circuit parameters, the inductance, the capacitance, and the resistance are distributed throughout the transmission line. If the transmission line is a conventional passive transmission line, the electrical output power of the transmission line is either equal to or less than the electrical input power, depending on the power loss of the transmission line.

If the transmission line is active, then the output power is greater than the input. In this case, the transmission line is considered as an amplifier. This is a distributed amplifier.

For example, an ordinary optical fiber cable is a passive transmission line for lightwaves. The output light of the optical cable is always less than the input light due to the cable loss. However, an erbium-doped optical fiber cable is different. The lightwave output of the cable is larger than the lightwave input. The input lightwaves, which are electromagnetic waves, are amplified. The erbium-doped optical fiber ca-

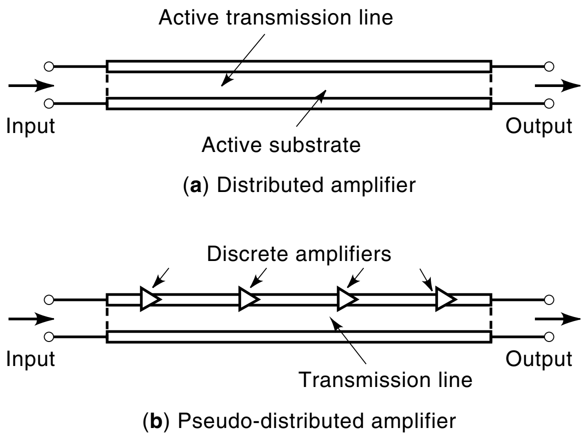

Figure 1. Generic configuration of distributed amplifiers. Signals to be amplified are fed at the left terminal. The signals are amplified during propagation on the line. The amplified signals exit from the right. (a) Distributed amplifier. The amplifier consists of a continuous active transmission line. (b) Pseudo-distributed amplifier. Lumped amplifiers are periodically loaded on a passive transmission line.

ble is an active transmission line and it is one type of distributed amplifier. A schematic diagram of a generic distributed amplifier is shown in Fig. 1(a). In this distributed amplifier, the transmission line is continuously loaded by the continuously distributed power-pumping active substrate.

In a pseudo-distributed amplifier, a number of discrete amplifiers are periodically loaded as shown in Fig. 1(b). The input power is amplified by these discrete amplifiers. Therefore, the output of the transmission line is greater than the input power.

The objective of the distributed amplifiers is to obtain a wide-frequency bandwidth with high amplification gain. The operating frequency ranges comprise radiofrequency (RF), microwaves, and lightwaves. Depending on the operating frequency range, the amplifier configurations differ significantly. The transmission line can be a two-wire line, a coaxial line, a waveguide, a microstripline, a coplanar waveguide, or an optical fiber cable.

The term *distributed amplifier* contrasts against the terms *discrete amplifier* and *lumped amplifier*. A lumped amplifier is represented in a block diagram as shown in Fig. 2. In a lumped or discrete amplifier, point A is the input, point B is the output, and the geometrical distance between points A and B is negligibly small in comparison with the operating wavelength. A distributed amplifier can also be represented by a block diagram as shown in Fig. 2, but the geometrical distance between actual point A and actual point B is comparable to the operating wavelength.

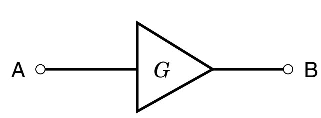

Figure 2. A block diagram representation of a discrete amplifier, a lumped amplifier, or a distributed amplifier. A generic symbol of a generic amplifier. G represents the gain of the amplifier. It can be the voltage, current, or power gain. A is the input, and B is the output terminal.

Continuous Active Diode Distributed Amplifiers

Activated or properly biased tunnel diodes, Gunn diodes, and varactor diodes are considered to be active diodes. When tunnel diodes and Gunn diodes are properly biased, these diodes exhibit negative resistance. Ordinarily a resistance is positive. A positive resistance consumes electrical energy. A negative resistance generates electrical energy. Therefore, if the amount of negative resistance is adjusted by material composition, configuration and the bias current, and if the circuit impedance of the transmission line is properly adjusted, then the active diode-loaded transmission line can amplify propagating electromagnetic waves on the transmission line. One possible biasing method is illustrated in Fig. 3(a). The transmission line is most likely a microstripline or a coplanar coupled waveguide. The microstripline is dc biased through an RF choke. If the active substrate is a tunnel diode of long degenerate or heavily doped *pn* junction, the properly forward biased *pn* junction exhibits negative resistance by the tunnel effect (1). If the active substrate is a long Gunn diode of properly doped *n*-type GaAs, the substrate exhibits negative resistance by the carrier momentum transfer effect (2).

The negative resistance can also be created by a properly biased and pumped long varactor diode junction. The varactor diode is a reverse biased *pn*-junction diode. This is a variable capacitance diode and the junction capacitance is varied depending on the bias voltage across the diode. The junction capacitance in the case of Fig. 3(b) is controlled by the dc bias and the pump oscillator voltage launched on the microstripline transmission line. Some varactor diodes work without dc bias. For optimal results, the pump oscillator frequency f_p is approximately twice that of the signal frequency f_s. When the pump oscillator frequency and phase are properly adjusted, the energy of the pump oscillator transfers to the signal through the variable junction capacitance and the signal waves are amplified as the waves propagate on the microstripline. The amplifier that functions by using a junction capacitance is termed a varactor parametric amplifier (1). The type of parametric amplifier shown in Fig. 3(b) is a traveling wave varactor parametric amplifier. Because the junction capacitance is continuously distributed along the microstripline, this is a distributed amplifier.

The pump oscillator wavelength and phase are adjusted. The pumping waves are synchronized with the input signal so that the junction capacitance of the varactor transmission line is always minimum where the signal voltage wave traveling is maximum.

Periodically Loaded Active Diode Distributed Amplifiers

A schematic diagram of a periodically loaded active diode microstripline distributed amplifier is shown in Fig. 4(a). The active diodes are either discrete tunnel diodes or Gunn diodes. Periodicity L is usually less than a quarter wavelength in order to avoid resonance. When the periodicity is made equal to either a quarter or a half wavelength the amplifier will be at resonance. In such cases, the frequency bandwidth narrows. It then may become unstable and oscillate. Resonance should therefore be avoided. One of the objectives of the distributed amplifier is to obtain a wide frequency bandwidth. Therefore it is safe to keep periodicity L at less than a quarter of a wavelength. The diodes must be correctly dc biased in the middle of the negative resistance region.

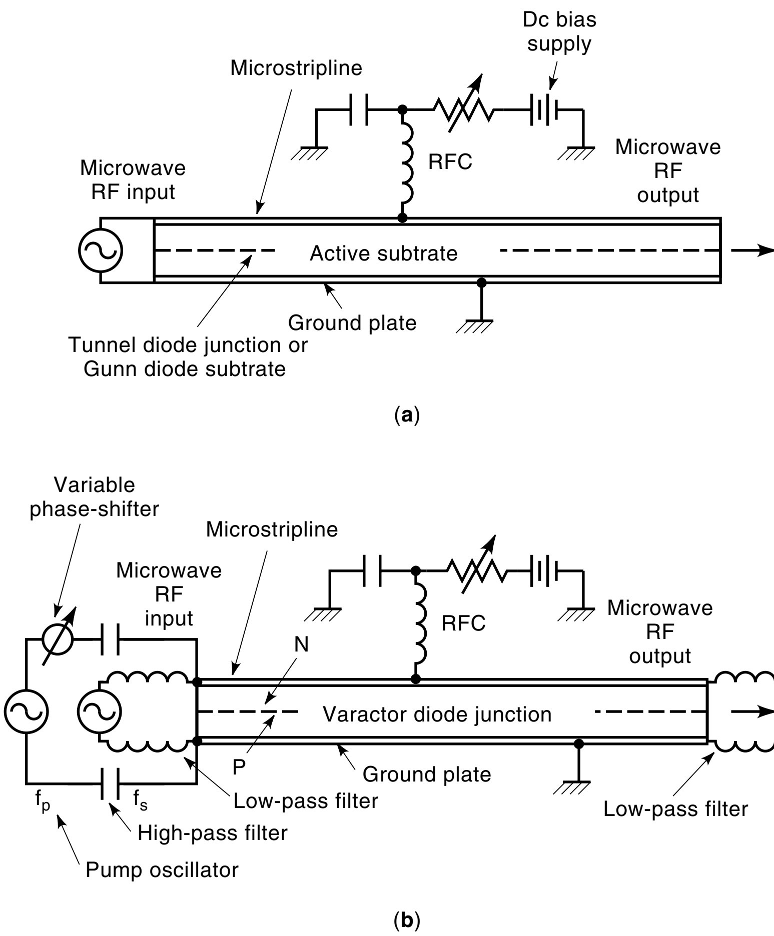

Figure 3. Continuous diode distributed amplifiers. Electromagnetic waves to be amplified are fed from the left end, and amplified signals exit at right. (a) Continuously loaded tunnel diode or Gunn diode transmission line distributed amplifier. The entire transmission line consists of a long and narrow section of tunnel diode junction or Gunn diode active region. (b) Continuously loaded varactor diode transmission line parametric distributed amplifier. The entire section of the transmission line consists of a reverse-biased variable capacitance *PN* junction.

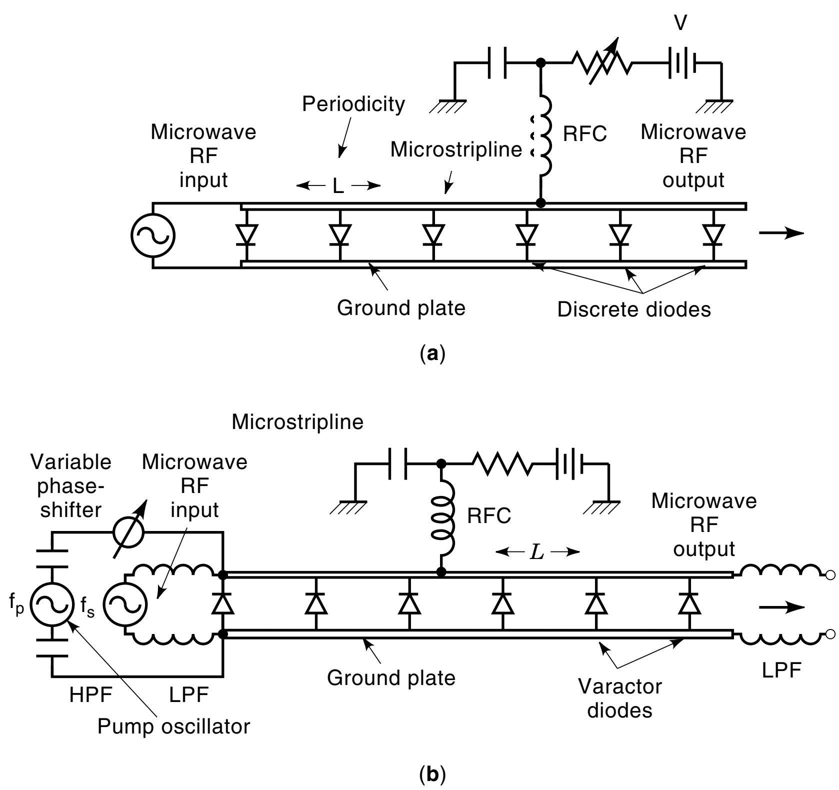

Figure 4. Periodically loaded active diode distributed amplifiers. (a) Periodically loaded active diode microstripline distributed amplifier. A microstripline is periodically loaded by active diodes with periodicity *L*. A properly biased active diode is capable of amplifying electromagnetic signals. (b) Periodically loaded active capacitive parametric distributed amplifier. A microstripline is loaded periodically by properly biased and pumped varactor diodes with periodicity *L*. Such varactor diode acts as a lumped amplifier.

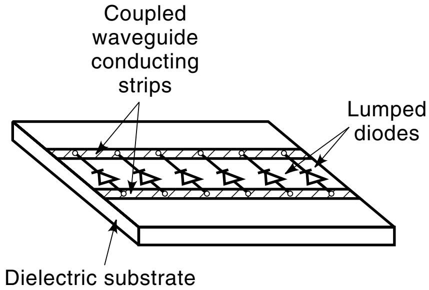

Figure 5. An example of a coplanar coupled waveguide distributed amplifier. This is an example of a case in which the transmission line is a coplanar coupled waveguide. Lumped diodes are mounted on it periodically.

A schematic diagram of a periodically loaded variable capacitance diode (varactor diode) parametric distributed amplifier is shown in Fig. 4(b). As seen from the diagram, varactor diodes are reverse biased by the dc bias supply and are pumped by the pump oscillator. Pump frequency f_p must be approximately twice that of the signal frequency f_s to be amplified. The pump wave on the line must be synchronized with the signal wave. Synchronization is accomplished using a variable phase shifter as shown in the pump oscillator circuit. The pump oscillator power is transferred into the signal through the varactor and the signal wave is amplified (1,2). The varactor diodes are pumped so that when and where the signal waves crest the junction capacitance becomes minimum. This phasing amplifies the microwave signal voltage. The transmission line can be a microstripline as shown in Fig. 4(b) or a coplanar coupled waveguide. An example of a coplanar coupled waveguide distributed amplifier is sketched in Fig. 5. As seen from this figure, fabrication of a coplanar coupled waveguide amplifier is easier than the microstripline amplifiers.

Continuous Transistor Distributed Amplifiers

A schematic diagram of a continuous transistor distributed amplifier is shown in Fig. 6. This is a field effect transistor (FET) of long configuration. Line length must be greater than the wavelength of the operating carrier signals. The microwave input signals are fed into the coplanar coupled wave-

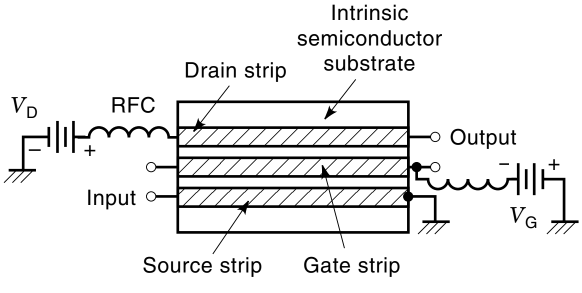

Figure 6. A schematic diagram of a continuous transistor distributed amplifier. This is a case of an extremely long gate field effect transistor. The length of the gate can be several wavelengths longer than the operating wavelength. As the input signals propagate on the gate-source line, the amplified output signals travel on the drain-gate line. The amplified signals exit at the right.

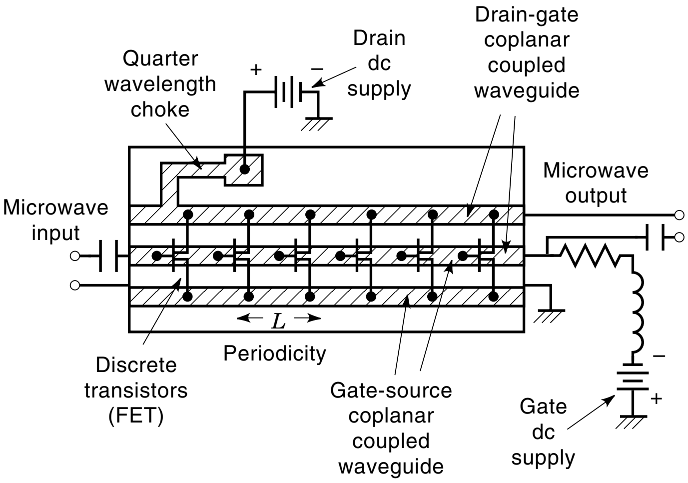

Figure 7. A schematic diagram of a periodically loaded transistor distributed amplifier. Discrete transistors are periodically loaded on a coplanar coupled waveguide. The input signals fed on the gate-source coplanar coupled waveguide are amplified as propagation on the line. The amplified output appears on the drain-gate coplanar coupled waveguide. The output propagates on the line and exits from the right.

guide, which consists of the gate strip and the source strip. As the input microwaves propagate along this input gate-source coplanar coupled waveguide, the amplified signal waves appear on the drain-gate coplanar coupled waveguide. Then the amplified microwaves exit at the end of the drain-gate coplanar coupled waveguide. The long transistor must be properly dc biased as shown in Fig. 6.

Periodically Loaded Transistor Distributed Amplifiers

A schematic diagram of a periodically loaded transistor distributed amplifier is shown in Fig. 7. To be qualified as a distributed amplifier, the length of a coplanar coupled waveguide must be longer than the wavelength of operating microwaves. If the length is very short it indicates simple parallel operation of the transistors. The input microwave signals are fed to the input of the gate-source coplanar coupled waveguide as shown in Fig. 7. As microwaves propagate down the gate-source waveguide, the amplified microwaves appear on the drain-gate coplanar coupled waveguide. The amplified microwaves propagate toward the output and exit from there. The coplanar coupled waveguides are periodically loaded by discrete field effect transistors. Periodicity L must be less than a quarter of a wavelength to avoid resonance. Otherwise, $n(\lambda_l/2) < L < (2n + 1)(\lambda_l/4)$ where λ_l is the transmission line wavelength and $n = 0, 1, 2, 3, \ldots$.

Thermionic Traveling Wave Distributed Amplifiers

A thermionic traveling wave amplifier, also called a traveling wave tube amplifier (TWTA), is a vacuum tube (2). Electrons are emitted from an electron gun into a vacuum as shown in Fig. 8. The emitted electrons are pulled by the anode (a helical transmission line) and focused by the longitudinally applied dc magnetic flux B. The electron beam is shot through the helix line and hits at an end-plate called an electron collector. The electron collector collects used-up electrons. The

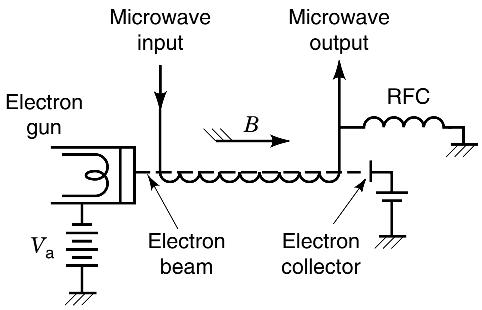

Figure 8. A schematic diagram of a thermionic traveling wave distributed amplifier. The pitch of the helical transmission line is adjusted so that the axial speed of microwave propagation on the line is almost equal to the speed of the electron beam. Under this condition, the kinetic energy of electrons is transferred into the traveling microwaves on the line, and the propagating microwaves are amplified.

helix transmission line is a distributed parameter transmission line. The pitch angle of the helix transmission line, the diameter of the helix, and the electron acceleration voltage are adjusted in such a way that the speed of the electron beam is equal to the axial propagation speed of microwaves on the helix transmission line. Then the kinetic energy of the electron beam is transferred to the microwave energy on the helical line through the distributed capacitance between the electron beam and the helical line. As the microwaves on the line and the electrons in the beam travel together, the microwaves are amplified and exit from the output of the tube as shown in Fig. 8 (2). The helical transmission line can be replaced by a meanderline or an interdigital transmission line (2).

Fiber Optic Distributed Amplifiers

A schematic diagram of a fiber optic distributed amplifier is shown in Fig. 9. The main part of this amplifier is a section of erbium-doped optical glass fiber cable (3). As seen from this figure, if a lightwave of proper wavelength is pumped into the fiber cable through a directional coupler from a pump laser, and the lightwave signal to be amplified is fed into the input of the fiber cable through an isolator, then while the signal lightwave is propagating in the fiber cable, the signal lightwave is intensified by the emission of radiation from the erbium atoms that are pumped by the lightwave (propagating in the fiber cable) from the pump laser. The pump lightwave travels with the signal lightwave and pumps the energy into the signal lightwaves through the stimulated emission of radiation from erbium atoms. This particular optical fiber is considered to be a distributed parameter transmission line amplifier for propagating optical electromagnetic wave signals.

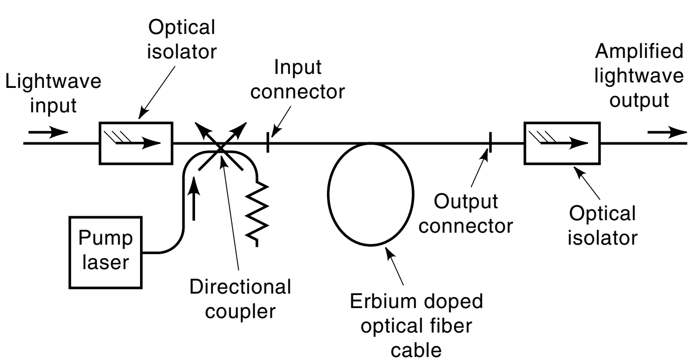

Figure 9. A schematic diagram of a fiber cable lightwave distributed amplifier. Active part is a long section of erbium-doped fiber cable. The erbium atoms are pumped by a light from the pump laser at left. The input lightwave signals are amplified by the stimulated emission of radiation from the pumped erbium atoms in the active fiber cable.

GENERAL GOVERNING EQUATIONS

Gain

A generic configuration of a distributed amplifier transmission circuit is shown in Fig. 10. In this diagram, R is the series resistance per meter of the distributed amplifier, L is the series inductance per meter of the distributed amplifier, $-G$ is the negative conductance per meter of the distributed amplifier, and C is the capacitance per meter of the distributed amplifier. The amplification constant of this amplifier is (1),

$$\alpha = \frac{\omega(CR - LG)}{\sqrt{2}\left\{(\omega^2LC + RG) + \sqrt{\begin{matrix}\omega^2(CR-LG)^2 \\ +(RG+\omega^2LC)^2\end{matrix}}\right\}^{1/2}} \text{[neper/m]} \quad (1)$$

where G is the magnitude of the negative conductance parameter. In a distributed amplifier, if the propagating power increase per meter is $\Delta P(W/m)$ and the propagating voltage increase parameter is $\Delta V(V/m)$, the magnitude of the negative conductance per meter is $G = 2\Delta P/(\Delta V)^2$ (S/m).

The phase constant of this amplifier is (1),

$$\beta = \frac{\left\{(\omega^2LC+RG)+\sqrt{\omega^2(CR-LG)^2+(\omega^2LC+RG)^2}\right\}^{1/2}}{\sqrt{2}} \text{[rad/m]} \quad (2)$$

If the length of the active region of the amplifier is ℓ m long then the voltage gain of the amplifier is

$$A = \alpha\ell \qquad \text{[neper]} \quad (3)$$

The total phase shift across the active region of the amplifier is

$$\Delta\phi = \beta\ell \qquad \text{[radian]} \quad (4)$$

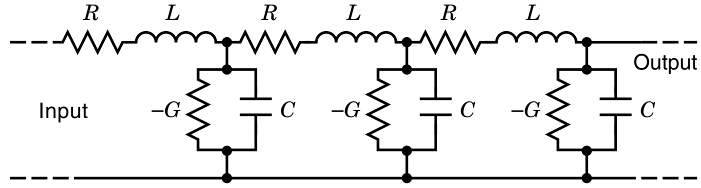

Figure 10. An equivalent circuit of a generic distributed amplifier. The negative conductance $-G$ generates energy and amplifies signals which are traveling on this line.

Frequency Bandwidth

In a generic distributed amplifier, the circuit parameters R, L, C, and G, are functions of operating frequency f. Therefore, the voltage gain of the amplifier is

$$A(f) = \alpha(f)\ell = \frac{(2\pi f)(C(f)R(f) - L(f)G(f))\ell}{\sqrt{2}\left\{((2\pi f)^2L(f)C(f) + R(f)G(f)) + \sqrt{\begin{array}{l}(2\pi f)^2(C(f)R(f) - L(f)G(f))^2 \\ +(R(f)G(f) + (2\pi f)^2L(f)C(f))^2\end{array}}\right\}^{1/2}} \quad (5)$$

At the edge of the frequency bandwidth at a frequency f',

$$A(f') = \frac{1}{\sqrt{2}}A(f_0) \quad (6)$$

where f_0 is the center frequency of the amplifier. Usually Eq. (6) is at least the second-order equation of f'. One root is f'_H, which is greater than f_0, and the other is f'_L, which is less than f_0. Then the frequency bandwidth is

$$\Delta f = f'_H - f'_L \quad (7)$$

Sensitivity

According to the *IEEE Standard Dictionary of Electrical and Electronics Terms* (4), sensitivity is defined as "the minimum input signal required to produce a specified output signal having a specified signal to noise ratio." This means that

$$\frac{P_sA_p}{KTBA_pF} = \frac{S_o}{N_o} \quad (8)$$

where A_p is the power gain of an amplifier, K is the Boltzmann constant 1.38054×10^{-23} J/K, T is the absolute temperature of the input circuit to the amplifier, B is the overall frequency bandwidth of the amplifier, P_s is the input signal power, F is the noise figure of the amplifier, and S_o/N_o is the signal-to-noise power ratio of the amplifier at the output. Then,

$$P_s = KTBF\frac{S_o}{N_o} \quad (9)$$

As "a specified signal to noise ratio," often

$$\frac{S_o}{N_o} = 1 \quad (10)$$

is used for the definition of the sensitivity of the amplifier. Then, the sensitivity is

$$P_s\Big|_{S_o/N_o=1} = KTBF \quad (11)$$

For a distributed amplifier, the value of B is obtained using Eq. (7). The value of the noise figure F can be obtained from the next section. Then the sensitivity is

$$P_s\Big|_{S_o/N_o=1} = \frac{N_o}{A_p} \quad (12)$$

where A_p is given by

$$A_p = \epsilon^{2\alpha\ell} \quad (13)$$

where $\alpha\ell$ is given by Eq. (5).

Noise Figure

Noise figure F of an amplifier is given by definition (1)

$$F = \frac{N_o}{KTBA_p} \quad (14)$$

where N_o is the noise output of the amplifier (W). For a distributed amplifier, both the frequency bandwidth B and the power amplification A are given by Eqs. (6) and (7), respectively.

Dynamic Range

A range of input signal level in which the gain of the amplifier is constant is termed the dynamic range of the amplifier. Usually, the gain of an amplifier is less at an extremely small input signal level or at a large input signal level.

In semiconductor distributed amplifiers, thermionic distributed amplifiers, or even in fiber optic distributed amplifiers, the values of L, C, R, and G are inherently functions of operating signal levels ν_s. Therefore, in Eq. (1),

$$\alpha(\nu_s) = \frac{\omega(C(\nu_s)R(\nu_s) - L(\nu_s)G(\nu_s))}{\sqrt{2}\left\{(\omega^2L(\nu_s)C(\nu_s) + R(\nu_s)G(\nu_s)) + \sqrt{\begin{array}{l}\omega^2(C(\nu_s)R(\nu_s) - L(\nu_s)G(\nu_s))^2 \\ +(R(\nu_s)G(\nu_s) + \omega^2L(\nu_s)C(\nu_s))^2\end{array}}\right\}^{1/2}} \quad (15)$$

If the gain constant in the linear region of the distributed amplifier is α_0, then the power gain of the amplifier is

$$A_{p0} = e^{2\alpha_0\ell} \quad (16)$$

where ℓ is the length of the active region of the distributed amplifier. In a large signal level ν_s the gain will be compressed due to saturation and

$$A_p(\nu_s) = e^{2\alpha(\nu_s)\ell} \quad (17)$$

where $\alpha(\nu_s)$ is given in Eq. (15).

If the gain compression of $-n$ dB is chosen, then,

$$-n[\text{dB}] = 10\log_{10}\frac{A(\nu_s)}{A_0} \quad (18)$$

or

$$n[\text{dB}] = 10\log_{10}e^{2\{\alpha_0-\alpha(\nu_s)\}}\ell \quad (19)$$

or

$$n[\text{dB}] = 8.686\{\alpha_0 - \alpha(\nu_s)\}\ell \quad (20)$$

In practice, $n = 1$ is often chosen, and the value of the input voltage for $n = 1$ is termed the input signal voltage at 1 dB compression point. The 1 dB compression point input signal voltage is then

$$\alpha(\nu_s) = \alpha_0 - \frac{1}{8.686\ell} \tag{21}$$

Stability

As seen from Eq. (1), a generic distributed amplifier is inherently stable. A controlling parameter in Eq. (1) is the magnitude of the negative conductance per meter G. Equation (1) does not show any singularity due to the size of G within the range of practical operation.

PERIODICALLY LOADED ACTIVE DIODE DISTRIBUTED AMPLIFIERS

Periodically Loaded Tunnel Diode Distributed Amplifiers

In a periodically loaded tunnel diode disturbed amplifier, a number of discrete tunnel diodes are periodically loaded on an RF transmission line as shown in Fig. 4(a). A generic volt ampere curve of a tunnel diode is shown in Fig. 11. This is a plot of the diode current and the voltage across the diode. When the diode is biased in a negative conductance region, the amount of the negative conductance is given by

$$G = \frac{\partial I}{\partial V} < 0 \tag{22}$$

In Fig. 12, an equivalent circuit of a discrete tunnel diode is shown. In this figure, L is the lead inductance, R_s is the spreading resistance, C_J is the junction capacitance, C_p is the package capacitance, and $-G$ is the negative conductance of the tunnel junction created by the tunnel effect. With the help of additional impedance matching components it is possible to tune out the inductances and capacitances; under a matched and tuned condition, the tunnel diode can be represented by a negative conductance of magnitude G_D.

The RF power gain due to a discrete negative conductance G_D, which is matched to a characteristic impedance of the transmission line Z_0, is (3),

$$A = \frac{1}{1 - G_D Z_0} \tag{23}$$

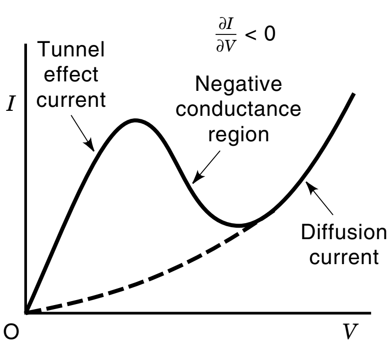

Figure 11. Generic volt-ampere curve of a tunnel diode. Note that this volt-ampere curve does not follow Ohm's Law. Note also the negative differential conductance at the mid-voltage region. This is a plot of the diode current versus the diode bias voltage relationship.

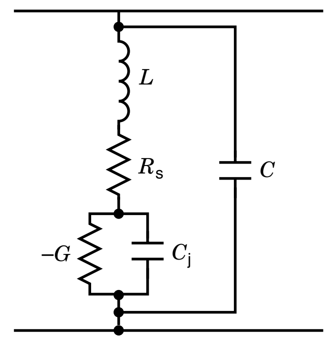

Figure 12. Equivalent circuit of a tunnel diode. This is for a packaged diode properly biased. C is the package capacitance; L is the lead inductance; R_s is the spreading resistance; C_j is the junction capacitance; and $-G$ is the negative conductance of the tunnel diode packaged.

At any diode in Fig. 4(a), half of the amplified power goes back to the input and the other half of the amplified power keeps traveling toward the output. Thus, actual power gain of traveling waves toward the output is

$$A^+ = \frac{1}{2(1 - G_D Z_0)} \tag{24}$$

If there are N diodes used in a distributed amplifier as shown in Fig. 4(a), the total power gain of the amplifier is

$$A_T = (A^+)^N = \frac{1}{2^N(1 - G_D Z_0)^N} \tag{25}$$

after matching and tuning.

For the impedance matching and tuning, in addition to attaching the impedance matching circuit components to the diode mount, the adjustment of periodicity together with the diode biasing must be done properly.

Periodically Loaded Gunn Diode Distributed Amplifiers

A volt-ampere characteristic of a generic Gunn diode is shaped similarly to that shown in Fig. 11 except that the negative conductance is smaller than that of a tunnel diode. The negative conductance of a Gunn diode is created by the transfer of the electronic momentum between a high electric field domain and a low field domain in the bulk of a semiconductor diode. The equivalent circuit of a Gunn diode is similar to the circuit shown in Fig. 12. Therefore, the principle of a periodically loaded Gunn diode distributed amplifier is similar to the principle of a periodically loaded tunnel diode distributed amplifier. Then the power gain equation of a Gunn diode distributed amplifier, which consists of N Gunn diodes in the negative conductance G_D and with the characteristics impedance Z_0, is

$$A_T = \frac{1}{2^N(1 - G_D Z_0)^N} \tag{26}$$

Periodically Loaded Varactor Diode Distributed Parametric Amplifier

When discrete variable capacitance diodes (varactor diodes) are periodically mounted on a transmission line as shown in

Fig. 4(b), RF voltage is amplified by the parametric effect of the junction capacitance. The voltage gain across a single parametric capacitance diode is given by Ref. 2.

$$A = \frac{\nu_p \sqrt{Q_i}}{4(v_o + v_{ro})} + \sqrt{Q_s} \quad (27)$$

where ν_p is the pump voltage across the junction capacitance of the varactor diode, v_o is the magnitude of the contact potential barrier of the diode, v_{ro} is the dc reverse bias voltage, and Q_i and Q_s are the quality factors of the idler circuit and the signal circuit per diode, respectively.

Usually in a parametric amplifier, the idler frequency shown in Fig. 4(b) is

$$f_i = f_p - f_s \quad (28)$$

and

$$f_p \simeq 2f_s \quad (29)$$

for a high gain (5). Then,

$$Q_i \simeq Q_s \quad (30)$$

Applying the same concept as was done in Eqs. (25) and (26), the total voltage gain of an N-diode distributed parametric amplifier is, after matching and tuning,

$$A_{\nu T} = \left\{ \frac{\nu_p \sqrt{Q_i}}{4(v_o + v_{ro})} + \sqrt{Q_s} \right\}^N \quad (31)$$

PERIODICALLY LOADED TRANSISTOR DISTRIBUTED AMPLIFIER

Similar concepts of Eqs. (25), (26), and (31) are applicable to a periodically loaded discrete transistor amplifier. The transistors can be either junction transistors or field effect transistors (6–8). If the s-parameter of the discrete transistor from the gate (or base) to the drain (or collector) is S_{21}, then, after impedance matching and tuning, the voltage gain of an n-transistor distributed amplifier is given by

$$A_{\nu T} = S_{21}^N \quad (32)$$

THERMIONIC DISTRIBUTED AMPLIFIERS

Thermionic distributed amplifiers are vacuum tubes that are called traveling wave tubes. A schematic diagram of a generic traveling wave tube is shown in Fig. 8. The principle of the traveling wave tube distributed amplifier was already briefly explained in this article. While microwaves travel along the helical transmission line with the axial propagation speed approximately equal to the speed of electron beam, the kinetic energy of the electron beam is transferred gradually into the propagating microwaves in the transmission circuit; hence the microwaves are amplified. The propagation constant of a traveling wave tube is given by (1,2)

$$\dot{\gamma} = \beta_e \left[-\frac{\sqrt{3}}{2}C + j\left(1 + \frac{C}{2}\right) \right] (\mathrm{m}^{-1}) \quad (33)$$

where β_e is the phase constant associated with the dc electron beam and

$$\beta_e \equiv \omega / u_0 \quad (34)$$

ω is the operating angular frequency and u_0 is the speed of the electrons in the beam. Term C in Eq. (33) is termed the gain parameter (1,2) and is given by

$$C^3 = \frac{Z_0 I_a}{4V_a} \quad (35)$$

where Z_0 is the characteristic impedance of the helical line, I_a is the dc electron beam current, and V_a is the acceleration anode voltage of the traveling wave tube.

If the length of the active interaction region on the helical transmission line is ℓ m long, then the voltage gain of this traveling wave tube is (2)

$$A = e^{(\sqrt{3}/2)C\beta_e \ell} \quad (36)$$

QUANTUM ELECTRONIC DISTRIBUTED AMPLIFIERS

A quantum electronic distributed amplifier can be a continuous configuration as shown in Fig. 9. If the signal to be amplified is a lightwave, then this distributed amplifier is a traveling wave laser. If the signal to be amplified is a microwave, then this distributed amplifier is a traveling wave maser. For a traveling wave maser, instead of the optical fiber cable, a microwave transmission line continuously loaded with maser material (such as a ruby or a rutile crystal) and a microwave local pump oscillator instead of the pump laser, are used.

At any rate, the gain constant of a traveling wave maser or laser distributed amplifier is given by (9)

$$\alpha = \frac{\omega}{2Q_{mo} \nu_g} \quad (37)$$

where ω is the angular frequency of the signal to be amplified, Q_{mo} is the quality factor/meter of the active cable and v_g is the group velocity of the signal in the cable. The quality factor Q_{mo} is given by

$$Q_{mo} = \omega \frac{W_{so}}{\Delta P} \quad (38)$$

where W_{so} is the electromagnetic energy of the signal stored per meter of the cable and ΔP is the signal power loss per meter of the cable.

The voltage gain of this continuously loaded distributed laser or maser amplifier is

$$A = \epsilon^{\omega \ell / 2Q_{mo} \nu_g} \quad (39)$$

where ℓ is the length of active part of the cable.

A quantum electronic distributed amplifier can be a periodical loading configuration as shown in Fig. 13. A microwave transmission line of a periodic structure is continuously loaded with an activated maser crystal and placed in a rectangular microwave waveguide. The pump power from a pump oscillator is fed to the rectangular waveguide to activate the maser crystal. The pumped-up maser crystal emits radiation when stimulated by the input microwave signals.

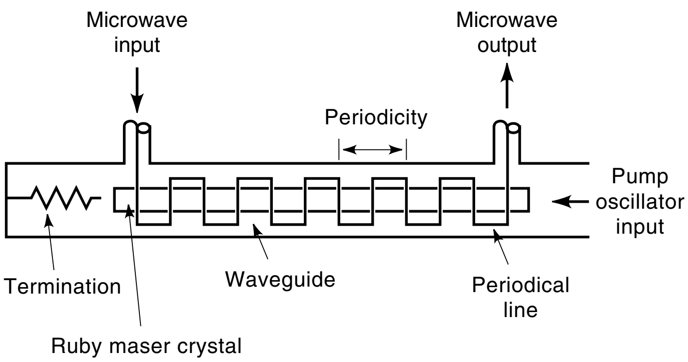

Figure 13. A schematic diagram of a periodically loaded quantum electronic maser distributed amplifier. The ruby maser crystal is pumped by the pump oscillator input in the waveguide. Microwave input signals are amplified by the stimulated emission of radiation from the pumped ruby maser crystal, while propagating down the meander line. The meander line is structured to lengthen the interaction time between the input signals and the stimulated emission of radiation.

The voltage gain of the periodically loaded quantum electronic distributed amplifier given by

$$A = \epsilon^{\omega\ell/2Q_{\mathrm{mp}}\nu_{\mathrm{g}}} \tag{40}$$

is in principle similar to the case of continuously loaded quantum electronic distributed amplifier where Q_{mp} is the quality factor within the periodicity of the periodical structure.

$$Q_{\mathrm{mp}} = \omega \frac{W_{\mathrm{sp}}}{\Delta P} \tag{41}$$

where W_{sp} is the signal energy stored within the periodicity of the structure of the transmission line and ΔP is the signal power loss within the periodicity.

EXAMPLES OF DISTRIBUTED AMPLIFIERS

RF Distributed Amplifiers

In practice, at RFs of less than 300 MHz, a distributed amplifier can be built using discrete components or surface mountable discrete components (10). An example of such distributed amplifiers is shown schematically in Fig. 14.

Discrete field-effect transistors (FETs) are sequentially excited through the gate delay line or the gate artificial transmission line and consist of C_{g}, $\frac{1}{2}L_{\mathrm{g}}$, L_{g}, L_{gg}, and R_{g}. These are discrete components. The C_{g} is a dc blocking input coupling capacitor, L_{g} is an inductor to produce desired phase delay between stages of the FET amplifiers, and R_{g} is the matched terminating resistor for the artificial transmission line. The idea is to generate RF traveling waves on the gate artificial transmission line. The L_{gg} is a stray inductance of the gate lead. In most cases L_{gg} is negligibly small at most RF frequencies. The terms R_{s} and C_{s} signify the source bias resistor and bypass capacitor and L_{dd} is the stray inductance of the drain of the FET. By making the drain lead as short as possible, it is possible to make L_{dd} negligibly small at RF frequencies.

The drain delay line or the drain artificial transmission line is formed by R_{d}, L_{d}, and C_{d}. The R_{d} is an impedance matched resistor to the drain artificial transmission line and L_{d} is the phase delaying inductor between stages. The value of L_{d} must be determined so that the phase of waves on the drain artificial transmission line synchronizes with the phase of waves on the gate artificial transmission line. The C_{d} is a dc blocking RF coupling capacitor to the output load. The transistors are biased through a radio frequency choke (RFC) and a decoupling capacitor.

Microwave Distributed Amplifiers

A variety of microwave frequency distributed amplifiers have been built in the past (10–12). In microwave frequencies, the distributed amplifiers take the forms of monolithically devel-

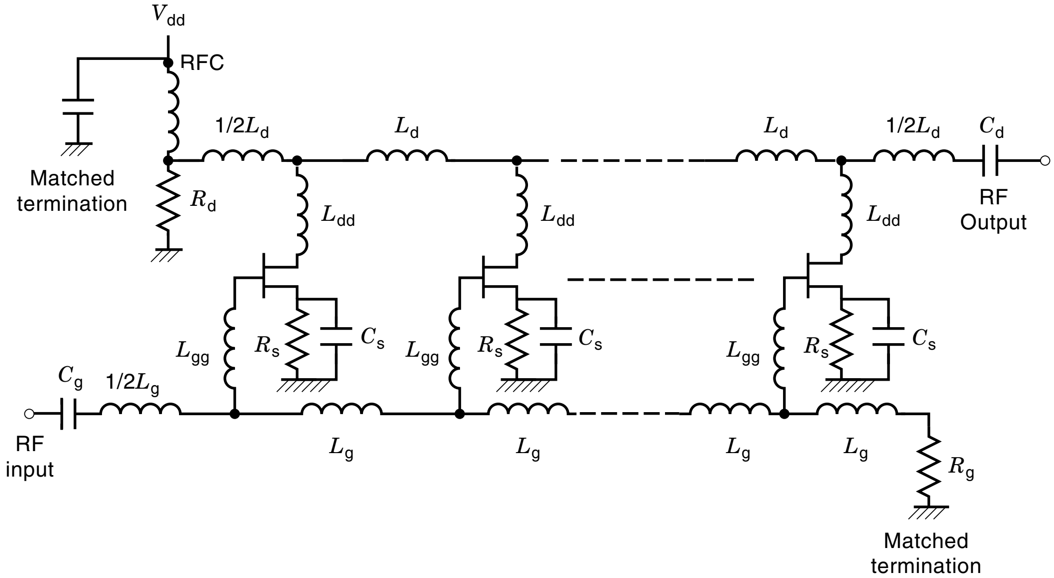

Figure 14. A schematic diagram of an example of an RF distributed amplifier. The input signals are successively and sequentially amplified by properly phased multistage FET amplifiers.

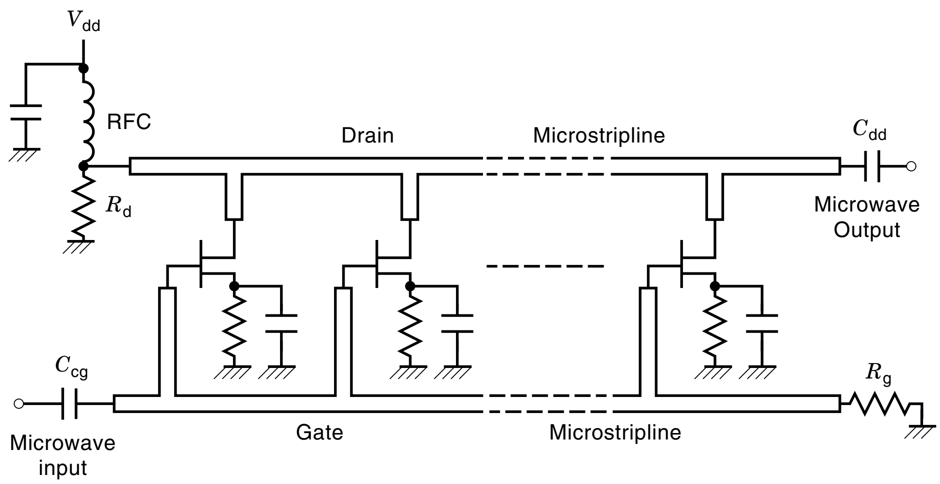

Figure 15. A schematic diagram of a microwave monolithic distributed amplifier. Both the gate and drain lines are microstriplines. The gate line feeds the FET sequentially. On the drain microstripline, the amplified signals are sequentially combined and propagate out at right.

oped integrated circuits as shown in Fig. 15 (for example). As is the case in Fig. 14, the microwave input signals to be amplified are fed to the gate microstripline with impedance-matched terminating resistance R_g through a dc blocking coupling capacitor C_{cg}. The gate of each FET, which is properly biased, is sequentially excited. Amplified microwave drain current propagates along the drain microstripline toward the output and it is coupled out to the output circuit through a dc blocking coupling capacitor C_{cd}. The drain microstripline is terminated with an impedance matched resistor R_d. If the circuit is properly balanced, current traveling toward C_{cd} adds in-phase, while current traveling toward R_d adds out-of-phase. This amplifier is actually a "current combiner." The drain microstripline is biased through a RFC and a bypass capacitor with V_{DD}.

At best, a distributed amplifier has only half the efficiency and requires twice the total gate width as a balanced amplifier, for the same gain (13). Gain, it should be noted, can be increased by adding more FETs—that is, by making it longer; best efficiency can be achieved, however, by optimizing the length. Once an optimal length is achieved, these distributed amplifiers can be cascaded in order to achieve the prescribed gain.

Because of losses in the amplifier, best performance can be achieved by tapering the gate (14), so as to "pre-distort" the applied gate voltage along the length of the amplifier, and aid in maintenance of a more steady voltage applied to the effective gate. Higher power, large signal amplifiers have also been designed and evaluated (15–19). Distributed amplifiers are limited in the amount of power they deliver, generally about 1 Watt (when using a 50 Ω transmission line). Lowering the impedance of the line can allow greater output powers but at the expense of a reduction in gain. Tapering the drain line has been found (20,21) to increase efficiency by improving the phasing of currents on the drain line.

Most microwave monolithic IC distributed amplifiers are of extremely wide frequency band even though total gain is not very high. They are also extremely compact. For example, Kimura and Imai (11) monolithically integrated a seven-stage distributed amplifier on a 1.5 mm × 2.5 mm integrated circuit (IC) substrate and reported that the flat gain over the frequency range 0 to 55 GHz with 6 dB noise figure was 9 dB.

Lightwave Distributed Amplifiers

The actual configuration of a lightwave distributed amplifier is shown in Fig. 9. These amplifiers are actually deployed to boost lightwave signals for a long-haul lightwave signal transmission such as in transoceanic lightwave cables. For example, the lightwave input signal to be amplified is 1500 nm wavelength (3). The pump laser is a 980 nm solid-state laser diode that feeds the pump power through a directional coupler to the main cable. The directional coupler is a pair of lightwave waveguides placed in proximity to each other so that the lightwaves can couple one waveguide to another. The end of the lightwave guide for the pump laser, which is the primary waveguide of the directional coupler, is reflectionlessly terminated using a lightwave absorbing component. The pump-laser light is fed into the main lightwave waveguide, which is the erbium-doped optical fiber. The pump laser light excites or pumps up the atoms of erbium to prepare for emission of radiation at 1500 nm. When these pumped up erbium atoms receive stimulating radiation of 1500 nm from the input lightwaves, these atoms emit radiation at the same 1500 nm wavelength. This is a laser amplifier. The emission of radiation continues as the input lightwave travels in the erbium-doped optical fiber. The emitted wave travels together with the stimulating lightwave. The amplified lightwave exits the output connector. The pump power is minimal at this point. It has been used in the amplification process. The signal output is taken out of the system through a bandpass filter for the signal lightwave. Any residual pump lightwave is rejected at the filter. The lightwave gain of 15 dB is reported for several meters-long erbium-doped plastic optical fiber cable.

The amplifier cable can be praseodymium-doped fluoride fiberglass cable with a wavelength of 1300 nm (3). The gain of 40 dB for several meter-long cable length is reported (3).

CONTINUOUS DISTRIBUTED AMPLIFIERS

Continuous Active Diode Distributed Amplifiers

In Fig. 5, it is possible to monolithically develop a continuous tunnel diode junction or Gunn effect diode contact between the two strips of metallization by removing all discrete diodes and using an intrinsic semiconductor substrate instead of the dielectric substrate. Then, if the conducting strips from the coplanar waveguide are properly biased at the negative resistance of the diode, the microwaves fed into one end of the coplanar waveguide will be amplified by the distributed negative resistance as it travels along the coplanar waveguide and the amplified microwave exits from the other end of the coplanar waveguide.

Continuous Transistor Distributed Amplifiers

A conceptual diagram of a continuous transistor distributed amplifier is shown in Fig. 6. It is desirable that the length of the microstrips must be longer than several wavelengths of the transmission line wavelength. The transmission line wavelength on the coplanar waveguide is smaller than the free space wavelength and inversely proportional to the square root of the effective relative permittivity of the substrate in the gap between the conducting strips. For a semiconductor substrate, it is not uncommon that the effective relative permittivity is 10 or higher.

Continuous Parametric Varactor Diode Distributed Amplifier

A conceptual schematic diagram of a continuous parametric varactor diode distributed amplifier is shown in Fig. 3(b). Using the same concept, an alternate method and more convenient approach to the monolithic integrated circuit technology is shown. Instead of using the microstripline as shown in Fig. 3(b), the configuration is changed to a coplanar waveguide as shown in Fig. 5. A long junction varactor diode is monolithically developed flatly between the gap of a long parallel metallization strip of the coplanar waveguide.

Continuous Ferrimagnetic Distributed Amplifiers

Space between the long gap of metallization strips of either the microstripline as shown in Fig. 3(b) or the coplanar waveguide as shown in Fig. 5, can be filled with a magnetized ferrimagnetic material or a ferrite. This is a ferrimagnetic continuous distributed amplifier (1,22). The nonlinear magnetism of a ferrite makes the system a variable inductance parametric amplifier when both the pump oscillator power and the signal power are launched into the same transmission line. The pump oscillator power then gradually transfers into the signals through the distributed nonlinear inductance of the ferrites as both the signals and the pump oscillator power travel together along the ferrite loaded transmission line.

CONCLUSIONS

Distributed amplifiers are electrical transmission lines with periodically or continuously loaded amplifiers. A feature of distributed amplifiers is the wide frequency bandwidth. The wide bandwidth amplifiers are capable both of having large channel capacity and of handling extremely short or fast pulses. Distributed amplifiers are useful for fast digital data transmission systems of gigabit rates. Distributed amplifiers can be made compact by the use of monolithic integrated circuit technology.

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