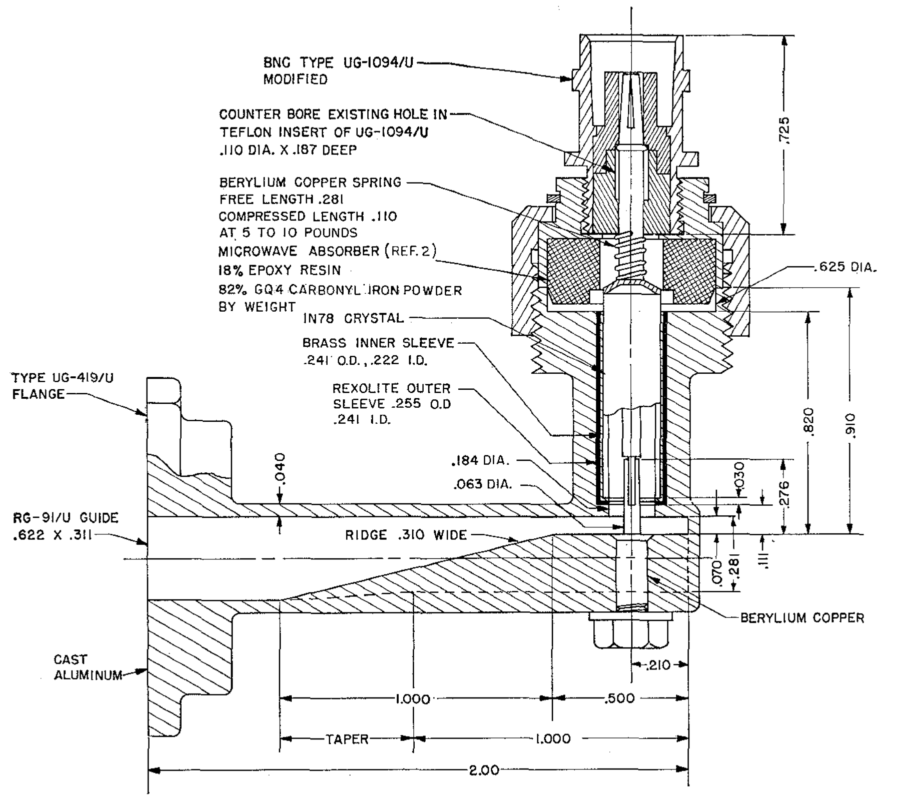

Fig. 1—KU band crystal mount (all dimensions in inches).

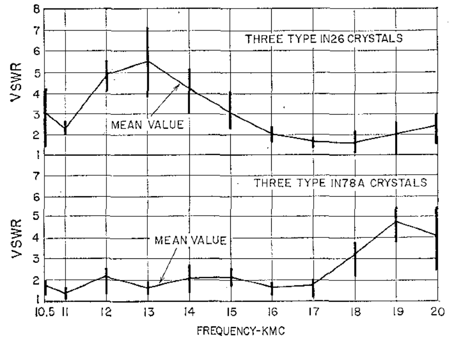

Fig. 2—VSWR at −36 dbm.

available did not permit a more extensive investigation.

The VSWR's of the mount, with two types of crystals, are shown in Fig. 2. The type 1N78A is a better match below 17 kmc, whereas the 1N26 crystal is better between 17 and 20 kmc. The mean tangential sensitivity vs frequency is plotted in Fig. 3, with two types of crystals. The short vertical lines indicate the spread in sensitivity of the group of crystals at each frequency. The arithmetic average sensitivity of the 1N78A crystals was −46.5 dbm, and that of the 1N26 crystals was −44.5 dbm.

In certain applications, such as in ratiometers, it is desirable that the sensitivity curves be parallel. The departure from this condition, known as "tracking error," was estimated from the data and is shown in Table I.

The choice of crystal type depends upon which frequencies are the most important in the particular application. The 1N78A crystals, designed for 16 kmc, have a higher

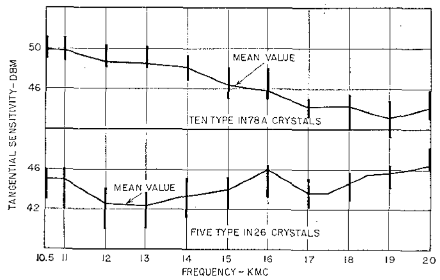

Fig. 3—Tangential sensitivity; video bandwidth 0.5 mc.

TABLE I
TRACKING OF SENSITIVITY OF CRYSTALS AND MOUNTS

Crystal			Tracking Error	
Number	Type	Number of Mounts	10.5–15 kmc	15–20 kmc
Ten	1N78A	One	2 db	2.7 db
Five	1N26	One	1.5 db	1.1 db
One	1N78A	Eight	1.5 db	2.5 db

sensitivity and a lower VSWR from 10.5 to 17.0 kmc, whereas the 1N26 crystals designed for 24 kmc are better from 17 to 20 kmc.

A. STANIFORTH
Radio and Electrical Engrg. Div.
Natl. Res. Council
Ottawa, Canada

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Proposed Parametric Amplifier Utilizing Ferroelectric Substance*

Ferroelectric substance has been utilized as nonlinear substance in parametric amplifiers.[1–4] However, all of these have been done at low-frequency regions. A surface-wave parametric amplifier employing ferroelectric substance in the microwave region has been proposed.[5]

The character of ferroelectric substance is not so clear at microwave frequencies as at lower frequencies. The nonlinearity caused by the domain wall motion cannot be utilized in the microwave region, because of the slow response of the wall motion.[6] However, the nonlinearity of $(BaSr)TiO_3$ has been measured in the microwave region (3000 mc).[7] This nonlinearity may be caused by the potential of the ionic atom (Ti atom or O atom). Therefore, we may consider the frequency limitation to depend upon the response of the motion of ionic atom. Infrared spectrum studies[8] show that the resonant wavelength of the Ti atom is in the order of 50 μ. From these results it seems feasible that some ferroelectric substance can be utilized in parametric amplifiers at microwave frequencies.

There are several problems to be considered in using ferroelectric substance for a parametric amplifier. First, three different frequencies (signal, idling, and pumping) should be supplied into the substance with minimum reflection. Second, the amplifier is desired to be operated with a low pumping power, especially at high frequencies.

Now, when microwave is applied to an isotropic, homogeneous material whose length is equal to an integer multiple of the half wavelength in the material, the wave reflected at the first surface is cancelled by the wave reflected at the other surface, and there is no reflected wave, provided that the material is lossless. When a TEM wave is used, *e.g.*, when the ferroelectric substance is set between two parallel plates or between the conductors of a strip line or coaxial line, the wave length in the material is expressed as follows:

$$\lambda = \frac{\lambda_{air}}{\sqrt{\epsilon}} \propto \frac{1}{\omega}. \qquad (1)$$

Therefore, when

$$\omega_{pumping} = \omega_{signal} + \omega_{idling}, \qquad (2)$$

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it is possible to make the length of the material equal to integer multiples of each half wavelength of the three waves, if the dielectric constant does not vary with the frequency. (Since the dielectric constant can be changed by dc bias voltage, the wavelength can be adjusted by dc bias. Consequently, the length of the material can be made equal to the multiples of the half wavelengths of all three frequencies.)

Suppose that a TEM wave is applied into a ferroelectric substance both of whose surfaces facing each other are parallel and are perpendicular to the propagating direction of the wave. The ratio, t, of the amplitude of the wave which passes through the substance and of the incidental wave is easily obtained.

$$|t| = 4\xi e^{-\alpha D}/\sqrt{(1+\xi)^4 - 2(1-\xi^2)^2 e^{-2\alpha D}\cos\theta + (1-\xi)^4 e^{-4\alpha D}}, \quad (3)$$

where ξ is $\sqrt{\epsilon_{air}/\epsilon_{substance}}$, D is the length of the substance, α is the attenuation constant of the substance, and $\theta = 4\pi D/\lambda$. λ is a wavelength in the substance.

On the other hand, the gain of the parametric amplification with respect to the signal wave in the substance is obtained from a modified theory of Tien and Suhl.[9] As for the attenuation constant of the signal wave, α, in (3) should be expressed by

$$\alpha = \alpha_1 - \alpha_g, \quad (4)$$

where α_1 is the true attenuation constant of the substance, and α_g is the gain and is expressed as follows:

$$\alpha_g = \frac{1}{4}\sqrt{\beta_s\beta_i}\,\frac{|\epsilon_p{}^0|}{\epsilon_0}, \quad (5)$$

where β_s and β_i are phase constants of signal wave and idling wave, respectively, ϵ_0 is the constant part of the dielectric constant, and $\epsilon_p{}^0$ is the amplitude of the alternating part of the dielectric constant caused by pumping wave. When $D = n\lambda/2$, (3) is simplified, and

$$|t| = 4\xi e^{-\alpha D}/\{(1+\xi)^2 - (1-\xi)^2 e^{-2\alpha D}\}. \quad (6)$$

These results show that amplification can be obtained when $\alpha_1 < \alpha_g$, where $|t|$ is the amplification of the amplifier. The maximum amplification is obtained when

$$e^{-\alpha D} = \frac{1+\xi}{1-\xi}. \quad (7)$$

In the practical design of the amplifier, the following must be considered:

1) *Roughness of the surface of the ferroelectric substance.* In order to make the length of the ferroelectric substance equal to multiples of the half wavelength, opposite faces perpendicular to the wave must be exactly parallel to each other. The roughness of these surfaces decreases the amplification. There are two possible effects. One of the effects is such that the roughness affects $|t|$ directly. The other is that the roughness decreases the amplitude of the pump wave in the substance and consequently decreases the gain α_g.

2) *Change of the dielectric constant with the microwave frequency.* Amplification was calculated with the assumption that the dielectric constant was independent of frequency. When the dielectric constant varies with the frequency, two undesirable effects take place. One is that the wavelength in the substance depends on the dielectric constant, so that similar effects as that of roughness occur. The other is that the gain α_g is decreased by the change of the dielectric constant with frequency. These were analytically calculated, but only numerical results will be shown.

Finally, some practical examples will be presented. First, let us consider the case when the nonlinear material is barium (73 per cent)-strontium (27 per cent)-titanate ceramics, which was measured by Davis, and Rubin at 3000 mc.[7]

Material ($BaTiO_3$, 73 per cent; $SrTiO_3$, 27 per cent) at 23°C with 5 kv/cm bias

Dielectric constant	about 3600
Dielectric loss	tan $\delta = 0.1$
	$\lambda_0\alpha_1 = 18.8$ nepers
Nonlinearity	$\epsilon_p{}^0/\epsilon_0$ per field strength $= 7$ per cent/(kv/cm)

Amplifier

Frequency		
signal	3000 mc	
idling	3000 mc or	6000 mc
pumping	6000 mc	9000 mc
Dimension		
thickness	0.1 mm	
length	0.83 mm ($=\lambda_s/2$)	
width	5 mm	

Results

Pumping voltage	
at minimum gain	2 kv/cm
at 20-db gain	2.4 kv/cm
at maximum gain	2.5 kv/cm
Pumping power	
at 20-db gain	4.7 kw at peak power

The roughness of surface must be within ± 0.01 mm.[10]

The change of the dielectric constant at the pumping frequency and at the signal frequency must be within 2.2 per cent.[10]

These results show that

1) material must be extremely small;
2) very precise work is necessary to fabricate the material;
3) rather high pumping power is necessary.

These undesirable facts are caused by the high dielectric constant and high dielectric loss of the material.

Next, let us consider the case when a new material, whose characteristic is shown in the following table, is used as a nonlinear substance. This material was originally proposed by Cassedy.[5] It is believed, however, that the material could not be easily prepared by suspending $(BaSr)TiO_3$ in a nonpolar binder as Cassedy proposed, because of the difference in the dielectric constant of $(BaSr)TiO_3$ and the nonpolar binder. It may be possible to obtain the desired material by mixing certain materials with $BaTiO_3$.

Material

Dielectric constant	about 100
Dielectric loss	tan $\delta = 0.01$
	$\lambda_0\alpha_1 = 0.31$ neper
Nonlinearity	$\epsilon_p{}^0/\epsilon_0$ per field strength $= 7/(\text{kv/cm})$

Amplifier

Frequency same as that for $(BaSr)TiO_3$	
Dimension of material	
thickness	0.1 mm
length	5 mm ($=\lambda_s/2$)
width	5 mm

Results

Pumping voltage	
at minimum gain	330 volts/cm
at 20-db gain	420 volts/cm
at maximum gain	460 volts/cm
Pumping power	
at 20-db gain	1.5 watts at peak power

The roughness of surface must be within ± 0.3 mm.[10]

The change in the dielectric constant at the pumping frequency and the signal frequency must be within 13 per cent.[10]

It is concluded that the new material would be suitable for an amplifier. The physical size of such material would not be too small for fabrication, and precise work will not be required. The pumping power would be only perhaps one to two watts.

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YOSHIMASA AOKI
Osaka City University
Osaka, Japan

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[10] In this case, the amplification coefficient $|t|$ does not decrease below half of that of the ideal case.

A Broad-Band Ferrite Reflective Switch*

Several types of reflective ferrite switches have recently been described in the literature.[1,2] These have typically made use either of the Faraday rotation effect or of a waveguide cutoff induced by a transversely-magnetized ferrite slab. A different and very simple type of switch, which exhibits similar reflective behavior, may also be obtained by the use of a short section of heavily-loaded (or filled) coax, stripline, or waveguide. Application of an axial magnetic field

* Received by the PGMTT, May 5, 1960.

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