A 12-GHz-Band FM Receiver for Satellite Broadcasting

By Y. KONISHI, N. HOSHINO
Y. UTSUMI, and H. MATSUMURA

An operational broadcast satellite system, which would provide television programming directly from a geostationary satellite for homes having television receivers equipped with a converter and a small antenna, is expected to be set up by Japan by the early 1980s. A design is described for a receiver suitable for this purpose; it is planned to be a low-noise, high-performance unit comparable in cost to conventional TV sets. Other topics covered include the image recovery theory (with consideration of the parametric effect of a mixer diode), the down-converter principles and construction, the low-cost highly stable local oscillator, and other sections of the receiver.

Introduction

"Yuri," a Japanese experimental satellite designed to help bring about an operational broadcast satellite system, was launched on 8 April 1978. "Yuri" is a medium-scale broadcasting satellite which can handle two color television channels at one time. An operational broadcast satellite system, in which television would be beamed directly by way of a geostationary satellite into homes where television sets are equipped with a converter and a small antenna, is expected to be set up by Japan in the early 1980s. With the advent of practical satellite broadcasting, low-noise, high-performance, and low-cost receivers will be in strong demand by the general public.

This paper presents the design of such a receiver as well as the image recovery theory with the parametric effect of a mixer diode taken into consideration. The construction and design principles of the down-converter with the frequency stability of 10^{-1} ppm as well as other sections of the receiver are described.

SHF-FM Receiver

SHF-FM receivers used for satellite broadcasting often have the configuration shown in Fig. 1. The system can be used for selecting one channel from "*n*" channels by changing the local oscillator frequency used for a second converter C_2. This design would be preferable for a direct home receiving system for future use in satellite broadcasting, if it is used with the conventional home television receivers.

In Fig. 1, any low-noise preamplifier (PA) such as a parametric, field effect transistor or a tunnel diode amplifier can be used. The noise performance of various preamplifiers is shown in Fig. 2. The noise figures of SHF down-converters, however, have recently been considerably reduced by means of image recovery techniques. In this case, a preamplifier is unnecessary as shown by the dotted line in Fig. 1, except in the case of an extremely low-noise receiver. To achieve such a low-noise receiver without preamplification, we have proposed the use of a converter with a planar circuit mounted in a waveguide. Using this technique, not only low-noise performance but also a low-cost, mass producible design has been obtained.

The Down-Converter

Image Recovery Technique

To achieve a low-noise down-converter using image recovery techniques, the converter must be designed so that it operates under the optimum reactive load viewed from a mixer diode at an image frequency. Several analyses of down-converters have been made, but they were treated under only limited image conditions (short, open, or matching).[1,2] For the case involving both the nonlinear conductance g and the junction capacitance C_j, the analysis of conversion loss and noise figure, with consideration of arbitrary image impedances and the effects of C_j, has never been published. The parametric effect caused by a junction capacitance of a mixer diode is a most important factor in determining the appropriate operation of the image recovery down-converter as described below.

Since a mixer diode can be represented by the equivalent circuit presented in Fig. 3, the operation of the down-converter can be explained by the equivalent networks shown in Fig. 4.

In the case where the pumping voltage $V_0 + V_1 \cos\theta$ is introduced into a diode, each of the expanded Fourier terms of g and C_j of Figs. 3 and 4 are expressed as follows:

$$g_{np} = \alpha \cdot i_0 I_n(\alpha V_1)$$

$$C_{np} = \frac{C}{2\pi}\int_0^{2\pi} \frac{\cos n\theta}{\sqrt{1-(V_0+V_1\cos\theta / V_\phi)}}\,d\theta$$

$$i = i_0(e^{\alpha V} - 1) \qquad (1)$$

where i is the diode current, I_n is the modified Bessel function, C is the junction capacitance with zero bias voltage, and V_ϕ is the junction voltage.

The conversion loss L_c between terminals S and i in Fig. 4 can be expressed as

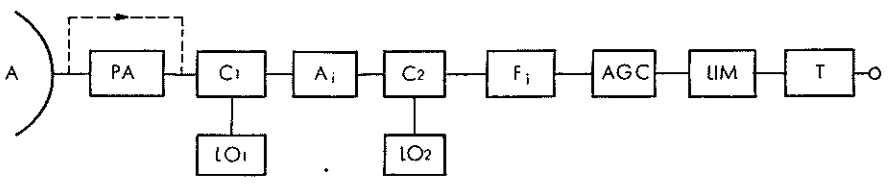
$$L_c = L_1 L_c' L_2$$

where L_1 and L_2 are the transmission losses caused by R_s in the signal and IF circuits, respectively, L_c is the conversion loss of the junction point of the diode and L'_c takes different values corresponding to the values of admittance y'_m viewed from the junction of a diode at an image frequency. Since y'_m is a function of the load reactance X_m connected to the diode, L_c can be obtained as a function of X_m. The computed results are shown in Fig. 5 for the following conditions: $i = i_0 e^{\alpha V}$; $\alpha = 34.7$; $i_0 = 1.5 \times 10^{-13}$ A; C and $C_c = 0.1$ pF; $V_\phi = 0.8$ V; $R_s = 2.5\ \Omega$; $f_p = 11.695$ GHz; $f_i = 380$ MHz.

At the point of image-open operation in Fig. 5, the value of L_c is a minimum due to the parametric effect of the junction capacitance C_j, so that L_1 has a large value. This is because the matched signal impedance becomes low. At the point of image-short operation, the effect of C_j can be neglected; therefore the value of L_c is nearly the same as that obtained without C_j.

The relation between the conversion loss and the noise performance must be considered. By denoting noise temperature ratios corresponding to the thermal noise generated at R_s in the signal, IF, and image circuits as t_{a_1}, t_{a_2}, and t_{a_m}, respectively, these values can be obtained from Fig. 4. As can be understood from Fig. 4, the noise temperature ratios take different values corresponding to the value of X_m (as shown in Ref. 3). The calculated values are shown in Fig. 6.

t_{a_m} takes large values near the point $x_m = 20\ \Omega$, since the admittance at the image terminal m' becomes small because of the parallel resonance at this point, which results in the generation of maximum thermal noise. This situation is shown in Fig. 6.



A : Receiving antenna
PA : Preamplifier
C1 : SHF down converter
Ai : IF amplifier
Fi : 2nd IF BP filter
AGC : Automatic gain control
LIM : Limiter
T : Signal processing circuit
LO1, LO2 : Local oscillators for SHF down converters

Fig. 1. Block diagram of the SHF-FM receiver.

Reprinted by permission from Laboratories Note No. 230 of the NHK (Nippon Hoso Kyokai or Japan Broadcasting Corp.), dated December 1978. The authors are with the Technical Research Laboratories of NHK, 1-10-11 Kinuta, Setagaya-ku, Tokyo 157, Japan.

The computed noise temperature ratio t'_{a_c} caused by shot noise generated in the mixer diode is also shown in Fig. 6. The physical meaning of the performance of t_{a_c} can be explained as follows. The input admittance of the C circuit of Fig. 4 viewed from the IF terminal is much smaller than $y'_i{}^*$ except near the point of image-open operation. Therefore, at this point the noise generated in the g circuit is amplified through the C circuit by the operation of the up-converter, and appears again at the IF terminal. Thus, t'_{a_c} takes maximum values near the point of image-open operation. This results in the increase of the noise figure of the image-open impedance.

The total noise temperature ratio is given by Eq. 2:

$$t = \frac{1}{L_c} + t_{a_1}) + t_{a_2} + t_{a_m} + t'_{a_c} \qquad (2)$$

The noise figure of the down-converter can be obtained by Eq. 3:

$$F = L_c\,(t + F_{IF} - 1) \qquad (3)$$

where F_{IF} is the noise figure of the IF amplifier connected to the down-converter. The computed values of F are shown in Fig. 6 using an IF amplifier having a 1.5-dB noise figure.

As can be seen in Fig. 6, F takes large values in the range of high image impedance. This is caused by the large value of t'_{a_c} as described above. For the above reasons, it is preferable to operate the converter under image-short conditions to obtain a minimum noise figure.

Down-Converter Design

A new technology developed by the authors, namely, a planar circuit mounted in a waveguide (PCMW),[3,4] is used in this down-converter. The converter uses a planar circuit sandwiched in a waveguide. On the planar circuit, proper patterns required for the function of the down-converter are fabricated by etching or punching techniques within an accuracy of 20 μm. An example of the construction[5] is shown in Fig. 7. Section F_R is used both to stop local oscillator power and to provide a power connection to the mixer diode. F_s is a band stop filter used to radiate pumping power to the outside, C is a capacitive strip for matching, D_m a mixer diode, and D_R a step recovery diode.

The planar circuit is designed by using equivalent network constants of several discontinuity parts as shown in Fig. 8. The network constants were obtained both theoretically and empirically with the constants of Fig. 8(e) being reported in Ref. 6. The effective length Δl prolonged is obtained by a variational method, with the result given in Eq. 4. Network constants of Figs. 8(a), (b), and (d) were obtained by empirical methods.

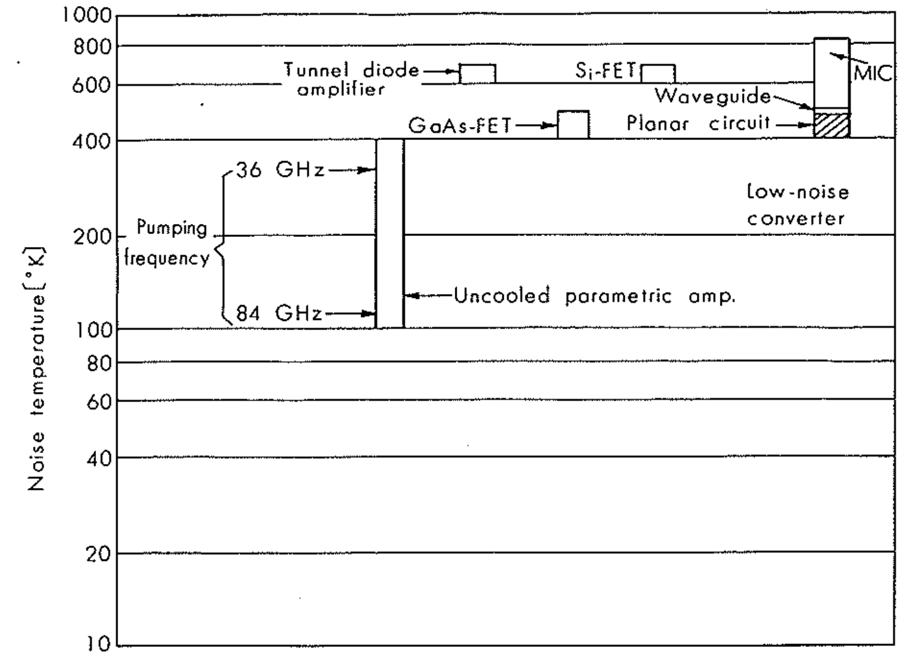


Fig. 2. Noise temperature of several kinds of 12-GHz-band receivers.

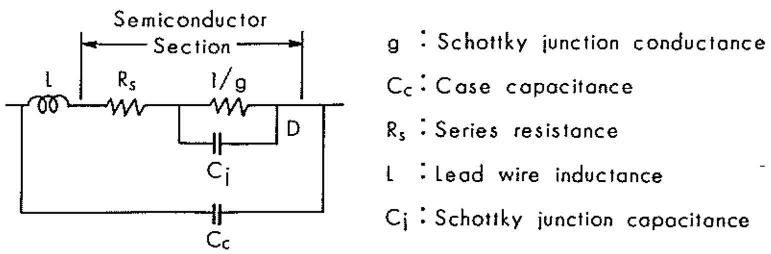


Fig. 3. Equivalent circuit of a mixer diode.

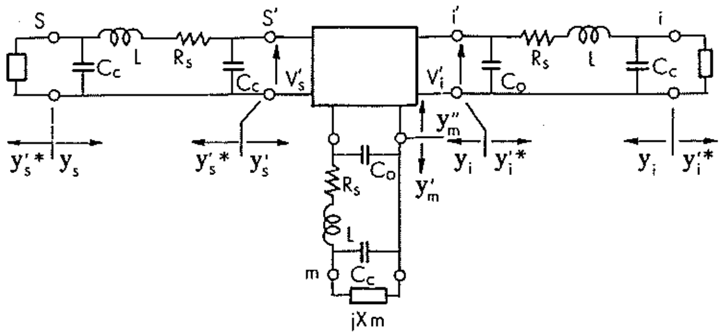


Fig. 4. Equivalent network of a down-converter.

$$\Delta l = \frac{\lambda_s\,\omega\,\mu_0 \sum_{n=1}^{\infty} \frac{1}{r_n^{(2)}} (e_{nt}^{(2)} \times h_{1t})^2}{2\pi Z_0} \qquad (4)$$

where

$$\iint_{s_2} |e_{nt}^{(2)}|^2\, ds = 1$$

$$\iint_{s_1} |h_{1t}|^2\, ds = 1$$

$$Z_0 = \frac{120\pi}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2}}$$

$$\lambda_s = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2}}$$

In these equations, s_1 and s_2 are sectional areas in regions 1 and 2; λ_0 is free space wavelength; $r_n^{(2)}$ is propagation constant of nth mode in the cutoff waveguide of region 2 in Fig. 8(c); λ_c is cutoff wavelength in ridge waveguide; $e_{nt}^{(2)}$ is normalized transversal electrical field in the cutoff waveguide of region 2 in Fig. 8(c); and h_{1t} is normalized transversal dominant magnetic field in the ridge guide.

Local Oscillator of Down-Converter

The local oscillator (LO) source is usually obtained from a Gunn oscillator or a step recovery diode. The Gunn oscillator should be locked in some manner such as by a dielectric resonator to stabilize its fre-

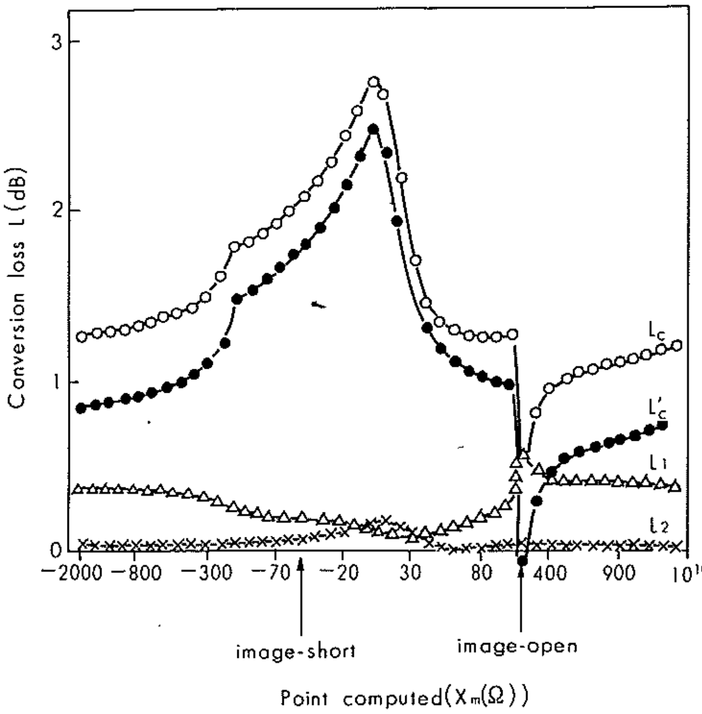


Fig. 5. Computer conversion loss.

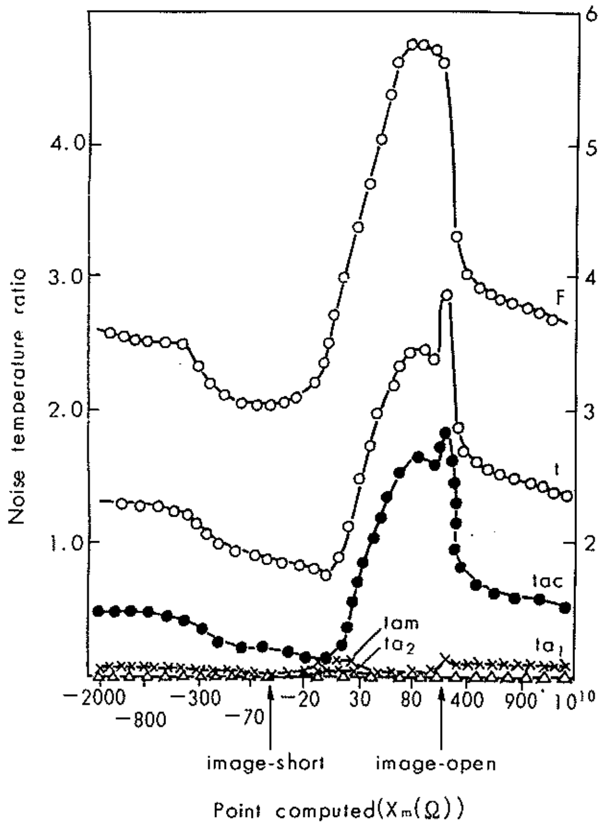


Fig. 6. Noise temperature ratio and noise figure.

quency. With this technique, the frequency deviation can be kept within 150 kHz for temperatures from −30 to +60°C. The step recovery diode is excited by a UHF source which is obtained by multiplying a crystal oscillator. The latter method should yield the lowest cost approach.

Recently, a temperature-stabilized *L*-band oscillator was developed by using bipolar transistors and a dielectric resonator. This was then used to drive a step recovery diode to a four-fold multiplication, as shown in the schematic diagram of Fig. 9. The resulting frequency deviation is less than 100 kHz at *X*-band in the range of −20 to +40°C. The dielectric resonator serves as a narrow bandpass filter inserted in the feedback loop of the transistor amplifier. This type of oscillator is quite suitable for mass production and is expected to provide a low-cost, stable oscillator operation.

IF Amplifier and Limiter

The frequency band of the IF amplifier should be chosen with consideration for the required bandwidth, noise figure, protection from other signals such as VHF and UHF bands, image frequency problems, and the distance between outdoor and indoor units. If the required bandwidth is reasonably narrow (about 200 MHz), f_i can be chosen between the VHF and UHF TV bands. In this case, the noise figure of the IF amplifier will be less than 1.5 dB, and the cost can be made low for a wideband gain matching operation.

Operation with weak signals is quite important for a limiter of a receiver for satellite broadcasting, because the receiver operates around the threshold levels in the rain. If the operation of the limiter is not sufficient, the AM components of noise are detected, resulting in the deterioration of the signal-to-noise ratio. The qualitative deterioration can be obtained from Eq. 5:

$$\frac{[SNR_0]}{SNR} = 1 + \frac{3\,\Delta f_m^2}{4 f_h^2\, A^2} \qquad (5)$$

where A is AM compression (for example, A = 10 for 20 dB compression); $[SNR]_0$ is signal-to-noise ratio of detected video signal for the case of an ideal limiter, with infinite A; SNR is signal-to-noise ratio for the case of a practical limiter, where A takes finite values; Δf_m is peak-to-peak frequency deviation; and f_h is highest video frequency. For example, when Δf_m = 12 MHz and f_h = 4.2 MHz, the deterioration of the signal-to-noise ratio takes the values shown in Table I.

For the above reason, it is preferable to design a limiter having AM suppression of more than 25 dB. PM to AM conversion is another important factor which should also

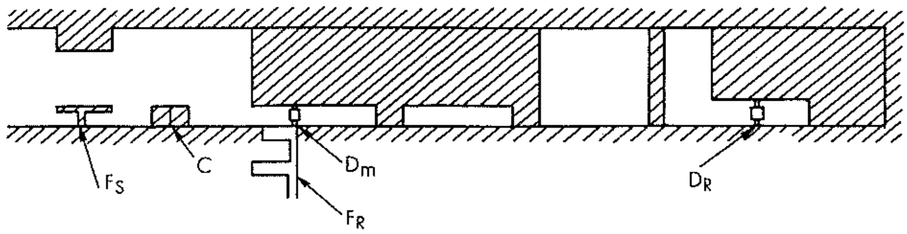


Fig. 7. An example of the construction of 12-GHz down-converter with a planar circuit mounted in waveguide.

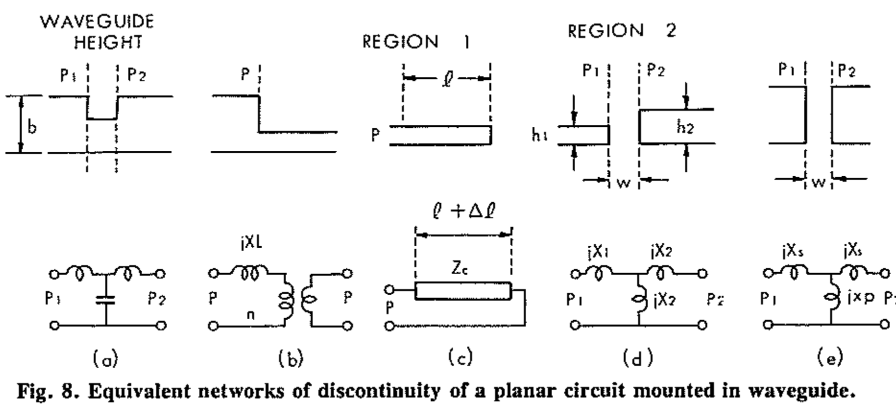
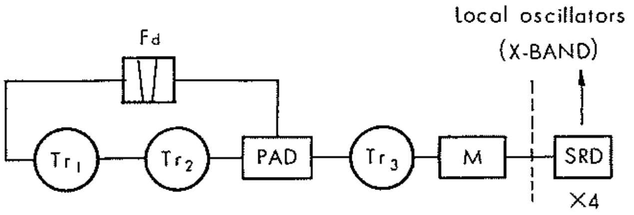


Fig. 8. Equivalent networks of discontinuity of a planar circuit mounted in waveguide.



$Tr_1 \cdot Tr_2$: Bipolar transistor(L band amplifier)
Fd : L band narrow BP filter with a dielectric resonator
PAD : Resistive divider
Tr_3 : Bipolar transistor(Buffer amplifier)
M : Matching circuit
SRD : Step recovery diode

Fig. 9. Local oscillator stabilized by using bipolar transistors and SRD.

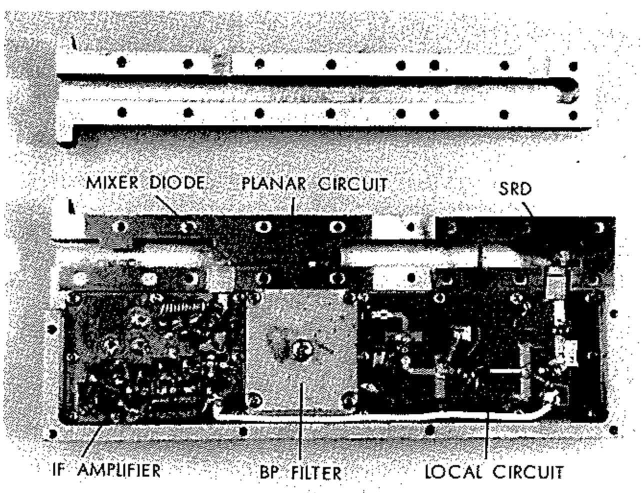


Fig. 10. SHF down-converter's outdoor unit developed by the NHK Technical Research Laboratories.

Table I. Relationship between deterioration of signal-to-noise ratio and AM compression.

Limiter Compression Ratio (dB)	$\frac{SNR_0}{SNR}$	$10 \log_{10}\frac{SNR_0}{SNR}$ (dB)
10	1.613	2.08
20	1.0613	0.258
30	1.00613	0.0265

The compression ratio of the limiter in decibels is given by $10 \log_{10} A^2$.

Table II. Practical values of antenna gain and efficiency.

Antenna diameter (m)	Gain (dB)	Efficiency (%)
0.6	34.9	54
1.0	39.6	63
1.6	43.9	64

be taken into consideration when designing the limiter.

The performance of the IF bandpass filter F, shown in Fig. 1, must be specified with consideration of the spectrum distribution and phase distortion. For the phase distortion, a surface acoustic wave (SAW) filter is preferable for future use because it exhibits linear phase performance.

The IF amplifier and limiter circuits must be simplified to achieve marketable low-cost receivers. A very simple circuit configuration was developed by combining a conventional diode limiter, a locking amplifier and a nonlinear feedback circuit. An AM suppression of more than 25 dB was obtained by means of this newly developed circuit.

Signal Processing Circuit

An FM signal appearing at the output of the limiter is demodulated to video and sound signals by a standard discriminator. To obtain an AM signal for a domestic TV receiver, video and sound signals should be remodulated respectively and then combined. A technique for doing this, the FM-AM direct converter, has been described in the literature.[6] With this circuit, it has become unnecessary to use a discriminator and remodulators, resulting in a simple, low-cost construction, although the sound subcarrier level becomes lower, requiring an additional amplifier for the sound subcarrier. It was, however, decided at the World Administrative Radio Conference — Broadcast Satellite Service (WARC-BS) of February 1977, to apply energy dispersal processing to practical satellite broadcasting. In this sytem of signal processing, an ordinary FM-AM converting circuit consisting of a discriminator and AM remodulator is employed rather than an FM-AM direct converting system. In the future, however, a simple FM-AM direct converting system which is applicable to the energy dispersal processing should be taken up as a study project. Meanwhile, a balanced feedback peak clamp circuit has been developed to remove the energy dispersal signal effectively.

The energy dispersal signal can be decreased by means of such a peak clamping method −30 dB at 15 Hz and −20 dB at 20 Hz. The circuit operates quite effectively even under a threshold level.

Receiving Antenna

A receiving antenna for satellite broadcasting should be capable of high gain, high efficiency, and production at low cost. To satisfy these considerations, a parabolic antenna can be fabricated of aluminum and fiber-reinforced plastic or mesh. The practical values of antenna gain and efficiency are shown in Table II.

For the reception of circularly polarized waves, a circular polarizer is connected to the top of a primary radiator. Such an antenna has more than 25-dB depolarization and less than 0.2-dB loss of antenna gain. With this antenna, either circular or linearly polarized waves can be received by simply rotating the polarizer about the axis of the primary radiator.

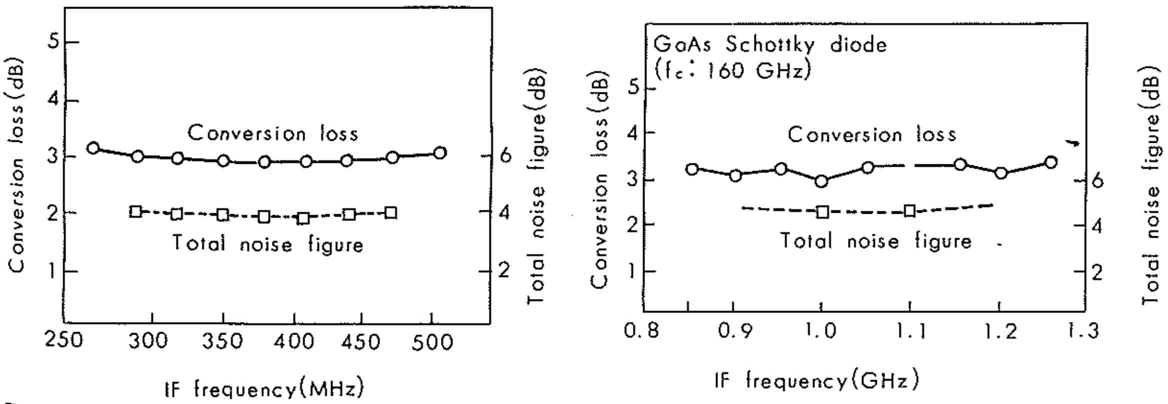


Fig. 11. Performance of a 12-GHz down-converter with a planar circuit mounted in a waveguide.

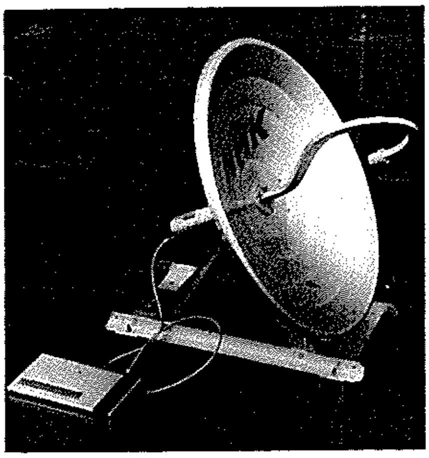


Fig. 12. Twelve-GHz-band FM receiver and 0.6-m antenna used for satellite broadcasting.

Experimental Results

The 12-GHz SHF receiver developed by NHK was constructed using a planar circuit mounted in a waveguide as shown in Fig. 10, and its performance is as given in Fig. 11. The complete SHF receiver developed for satellite broadcasting is shown in Fig. 12. In quantities of 100,000 the cost of this receiver including antenna and outdoor and indoor units is expected to be 70 to 80 thousand yen (approx. $290 to $340). This receiver was used to receive the signal from the Communications Technology Satellite (CTS) in the U.S. under the jointly sponsored NASA-NHK experiment entitled Advanced Ground Receiving Equipment:* In this experiment, we have received signals with weighted signal-to-noise ratios of 49.5 dB and 45 dB by using 1- and 0.6-m antennas under the condition of 58.5-dBW EIRP (effective isotropic radiated power).

Conclusion

A low-noise, low-cost receiver for SHF satellite broadcasting reception was developed successfully by the authors at the NHK Technical Research Laboratories. The indoor unit, consisting of an IF amplifier, a limiter, a signal processing circuit, and an appropriate power supply may be assembled as an integral part of the domestic TV receiver in the very near future. This will also greatly contribute to the reduction of the receiver's production cost. In the future, the integrated circuits will be introduced to the IF circuits both in the outdoor and indoor units, and this also will help lower the receiver cost if mass produced.

Advances in the development of microwave semiconductors such as FETs and bipolar transistors should always be taken into account and these devices should also be introduced if available economically. In order to make the receiving antenna inexpensive, the study of primary horns is essential, with the target of simple antenna construction with high efficiency.

*This is a joint experiment by NASA and the Technical Research Laboratories of Nippon Hoso Kyokai (NHK), Japan. The participation of NHK is being sponsored by the Radio Research Laboratories of the Ministry of Posts and Telecommunications, Japan.

References

1. R. J. Mohr, et al., "A Note on the Optimum Source Conductance of Crystal Mixers," *IRE Trans., Vol. MTT-8*, 622–627, Nov. 1960.
2. M. R. Barber, "Noise Figure and Conversion Loss of the Schottky Barrier Mixer Diode," *IEEE Trans., Vol. MTT-15*, 629–635, Nov. 1967.
3. Y. Konishi, et al., "New Microwave Components with Mounted Planar Circuit in Waveguide," *NHK Laboratories Note*, Serial No. 163, Mar. 1973.
4. Y. Konishi, et al., "The Design of Planar Circuit Mounted in Waveguide and the Application to Low Noise 12 GHz Converter," 1974 IEEE S-MTT International Microwave Symposium.
5. Y. Konishi, et al., "The Design of a Bandpass Filter with Inductive Strip — Planar Circuit Mounted in Waveguide," *IEEE Trans. on MTT, Vol. MTT-22*, 869–873, Oct. 1974.
6. Y. Konishi, et al., "Proposed SHF FM Receiver for Satellite Broadcasting," ICMCI, 1973.