A 22-GHz-Band Low-Noise Down-Converter for Satellite Broadcast Receivers

Kazuo Imai and Hisao Nakakita

Abstract—**A simple low-cost and high-performance 22 GHz band down-converter is developed for a future direct-to-home satellite broadcasting system. The down-converter consists of a low-noise HEMT preamplifier, an image recovery mixer with a novel structure using dielectric resonator filters, a 21.4 GHz GaAs FET oscillator stabilized by a dielectric resonator, and an IF amplifier. These components are fully integrated using MIC technology into a small size. A total noise figure of less than 2.8 dB is obtained over the 22.5–23.0 GHz frequency range. The local oscillator achieves a frequency variation of less than 600 kHz$_{\text{p-p}}$ over a temperature range of $-20°$ to $+60°$C.**

I. Introduction

The frequency band 22.5–23.0 GHz was allotted to ITU Regions 2 and 3 for direct-to-home satellite broadcast services by the World Administrative Radio Conference (WARC) in 1979. The band is expected to be used for new media services such as integrated services of digital broadcasting (ISDB) and digital high-definition TV (HDTV) in the future. In order to realize and popularize these new services, it is important to develop simple, low-cost, low-noise down-converters for the front ends of home receivers.

There have been many papers on integrated receivers including amplifiers, mixers and oscillators around the 22 GHz band. The development of these components, however, has been concentrated only on professional use such as terrestrial communications [1], [2], satellite communications [3], [4], radio astronomy [5], and radars [6]. An example of a down-converter for home receivers for a 22 GHz band satellite broadcasting system has been reported by Utsumi and Imai [7]. This is a mixer-input down-converter with a noise figure of less than 5.2 dB that uses a planar circuit mounted in a waveguide and a Schottky barrier diode. With the recent advances in semiconductor and material technologies, low-noise devices and low-loss materials applicable up to the millimeter frequency range have been developed [8]–[11]. A lower noise figure is expected by using these devices. Microwave integrated circuits (MIC's) currently use two-port devices to fulfill the demands of cost and performance. Monolithic microwave integrated circuits (MMIC's) [2]–[4], [6] are attractive for high-volume applications.

Manuscript received October 3, 1990; revised February 7, 1991.
The authors are with the Science and Technical Research Laboratories, Japan Broadcasting Corporation, (NHK), 1-10-11 Kinuta, Setagaya-ku, Tokyo 157, Japan.
IEEE Log Number 9144271.

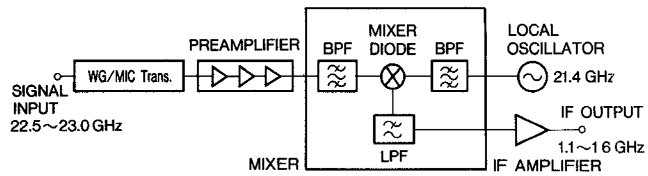


Fig. 1. Block diagram of 22-GHz-band low-noise down-converter.

This paper describes the design features of a 22 GHz band down-converter using MIC technology [12]. The purpose of this work is to develop a receiver front end that offers not only high performance but also low cost. In an attempt to achieve a reasonable cost, only commercially available semiconductors and dielectric materials for 12 GHz band direct-to-home broadcast receivers have been employed. The circuits have been carefully designed to fully extract the capabilities of these parts. The main features of this work are as follows:

1) Low-cost HEMT's now being mass produced for 12 GHz band receivers have been employed for a 22 GHz band low-noise amplifier (LNA). The noise performance of the LNA is suitable for satellite broadcasting systems.
2) An image recovery mixer with a novel structure using dielectric resonators (DR's) has been proposed. Using this structure, the image short condition for minimum noise figure is easily achieved.
3) A highly stabilized 21.4 GHz GaAs FET oscillator has been realized by using a high-Q DR specially prepared for the mounting structure of the DR.

On the basis of this approach, a low-noise and highly stable 22 GHz band down-converter has been developed. Additionally, the material cost of the 22 GHz band converter is equal to or less than that of a 12 GHz band converter for satellite broadcasting.

II. Configuration of 22 GHz Band Low-Noise Down-Converter

A block diagram of the 22 GHz band low-noise down-converter is shown in Fig. 1. The converter accepts an RF input of 22.5–23.0 GHz and generates an IF output of 1.1–1.6 GHz. The local oscillator frequency is 21.4 GHz.

The waveguide to MIC transition uses an E-field probe. This does not require the dc blocking circuit at the first stage of the preamplifier. The transition has demonstrated an insertion loss of less than 0.2 dB and a return loss of more than 20 dB over the 22.5–23.0 GHz band.

The three-stage low-noise preamplifier decides the noise figure of the converter. The mixer uses a Schottky barrier mixer diode and DR's. The local oscillator generates a 21.4 GHz signal directly from a GaAs FET and is stabilized by a DR. The IF amplifier (IFA) consists of three packaged MMIC's. The noise figure of the IFA is less than 2.5 dB, and the gain is 32 dB over the IF band. All these components are constructed on MIC substrates.

The design details of the preamplifier, mixer, and local oscillator and the overall performance of the converter will be discussed in the following sections.

III. Low-Noise HEMT Amplifier

To achieve low cost and low noise, the device chosen for this study was a 0.3-μm-gate-length HEMT (NE202, NEC), which is commonly used in receivers for 12 GHz band direct-to-home satellite broadcasting [13].

The S parameters of the HEMT chip were measured around the 22 GHz band, as well as those of a stripline-type packaged HEMT, to investigate the feasibility of using packaged devices. The measured S parameters of both the HEMT chip and the packaged HEMT are shown in Fig. 2. The values of the packaged HEMT change rapidly with frequency owing to the parasitic susceptances of the package, while those of the HEMT chip vary only slightly. From the measured data, we decided to use HEMT's in chip form for easy impedance matching.

Measurement of the noise parameter necessary for LNA design was omitted, since the loss of tuners makes it hard to obtain accurate values of noise parameters in the 22 GHz band. The optimum impedance for a minimum noise figure was obtained by adjusting the matching network for maximum gain.

The LNA is realized by the following procedure: Based on the measured S parameters, the input and output matching networks with bias circuits of a single-stage amplifier are designed to maximize the gain. A microstrip line on a 0.38-mm-thick alumina substrate is used as the transmission medium. The three-stage amplifier is assembled as a series of cascading stages and the matching networks of the first and second stages are tuned to minimize the total noise figure by connecting gold ribbons to the patterns. As a small modification of the patterns is needed for the minimum noise figure, the noise optimum impedance is considered not to be so different from the conjugate of S_{11}.

The LNA shows a gain of 21.5 dB and a noise figure of 2.6–2.7 dB over the 22.5–23.0 GHz range.

IV. Mixer

A. Novel Structure of Image Recovery Mixer

The newly proposed structure of the image recovery mixer is shown in Fig. 3.

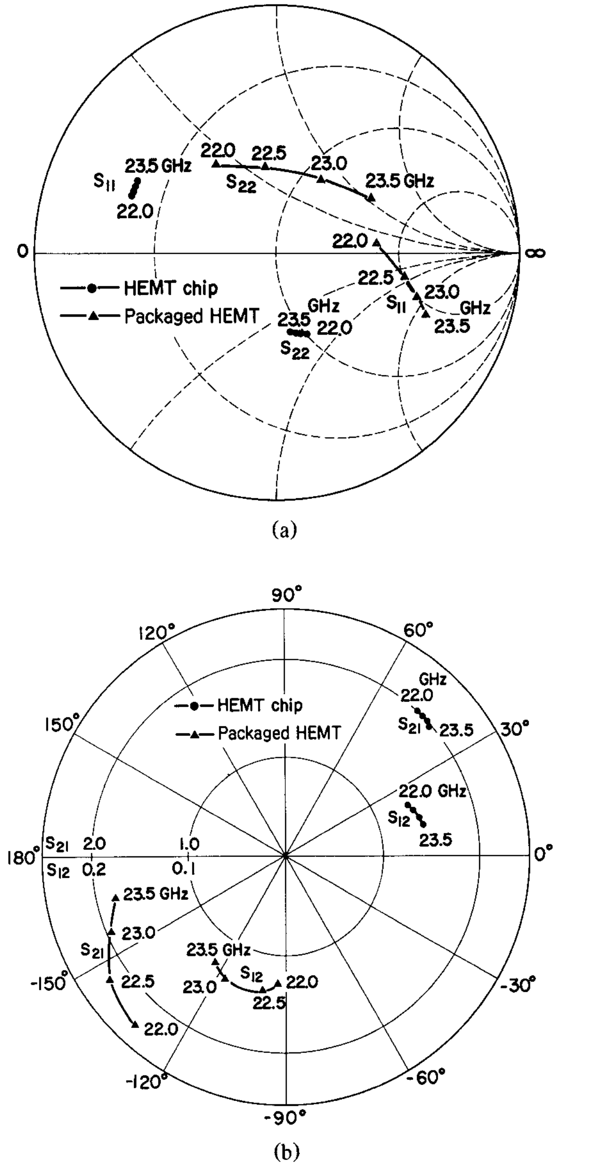


Fig. 2. S parameters of HEMT. (a) S_{11}, S_{22}. (b) S_{21}, S_{12}.

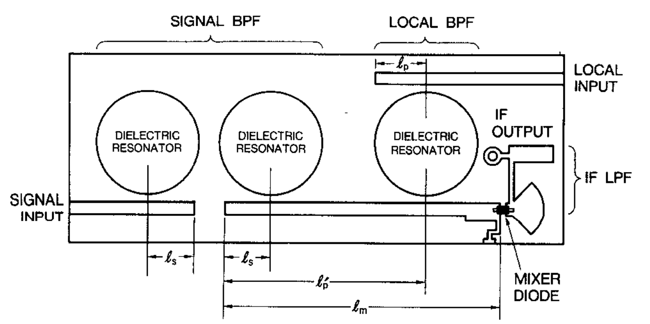


Fig. 3. Construction of mixer.

The band-pass filters (BPF's) for both the signal and local oscillator frequencies consist of DR's. A GaAs Schottky barrier mixer diode is mounted at the end of the microstrip line magnetically coupled to DR's excited in cylindrical $TE_{01\delta}$ mode. For tight coupling between the microstrip lines and DR's, the later are placed at odd-number multiples of a quarter of a guided wavelength at their resonant frequency from the open end of the microstrips. The distances l_s, l_p, and l'_p are $l_s = \lambda_{gs}/4$, $l_p = \lambda_{gp}/4$, and $l'_p = 7\lambda_{gp}/4$, respectively, where λ_{gs} and λ_{gp} are the guided wavelength of the microstrip line at the signal frequency and that of the local frequency, respectively.

It has been shown through noise analysis [7] that the noise figure of a mixer with a Schottky barrier diode is greatly affected by the shot noise generated at the Schottky junction and that this noise is amplified by the parametric action of the junction capacitance. In order to suppress this parametric effect and lower the noise figure, the impedance of the external circuits of the mixer diode should be nearly zero at the image frequency f_m $(=2f_p - f_s$, where f_p is the pumping frequency and f_s is the signal frequency). In this mixer, the above condition is achieved as follows.

The length l_m of the microstrip line connected to the mixer diode is an odd-number multiple of $\lambda_{gm}/4$, where λ_{gm} is the guided wavelength of the microstrip line at the image frequency. DR's for signal BPF and local BPF are magnetically coupled to this line, but the impedance of the line seen from the diode at the image frequency is decided solely by the length l_m when the Q_0's of the DR's are sufficiently high and the DR's are completely off-tuned at the image frequency. Thus, the construction of DR's in this mixer does not destroy the image short condition, and the image short can be easily determined by the stripline length.

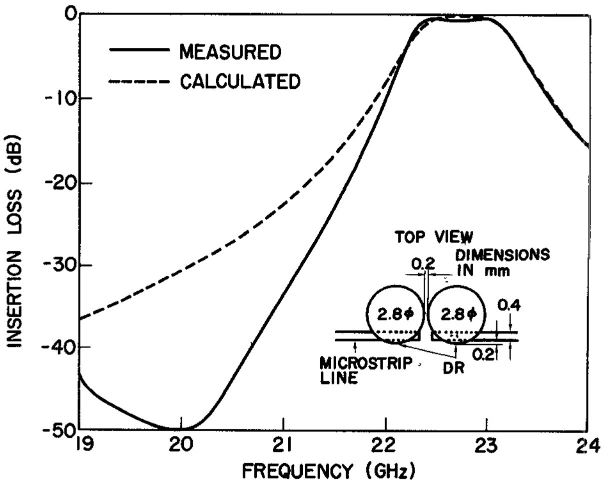


Fig. 4. Performance of signal band-pass filter.

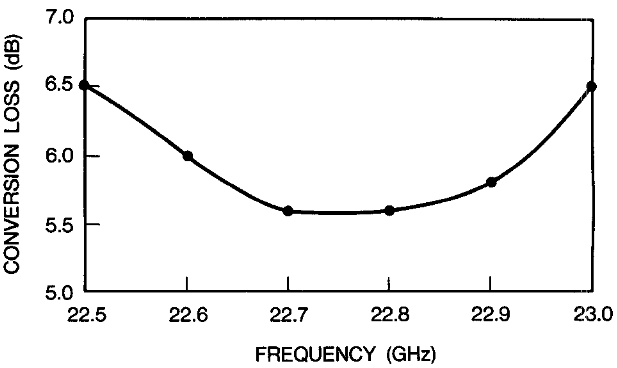


Fig. 5. Conversion loss of mixer.

B. Performance of Mixer

The mixer circuit in Fig. 3 is fabricated in a brass housing whose dimensions are small enough for all waveguide modes to be below cutoff. An alumina substrate was selected for mechanical strength of beam-lead diode bonding, and a thickness of 0.38 mm was used. The DR is made of $Ba(Zn_{1/3},Nb_{2/3})O_3$ [10] and is 2.8 mm in diameter and 1.0 mm thick. The relative dielectric constant, ϵ_r, is 31 and the unloaded Q factor is 3000 in the 22 GHz band.

The BPF design is based on the transformation from a low-pass prototype to a band-pass filter, as described by Matthaei *et al.* [14]. The signal BPF using two DR's is designed to have a Butterworth response with a center frequency of 22.75 GHz and a bandwidth of 1 GHz. Referring to the formulas in [14, p. 432], Q_E (the coupling between the DR and the microstrip line) and k_{12} (the coupling between the two DR's) are determined as follows with the prototype elements $g_0 = g_3 = 1.0$ and $g_1 = g_2 = 1.414$;

$$Q_E = 32 \qquad k_{12} = 0.03.$$

These couplings are obtained by positioning the DR's on an MIC substrate as illustrated in Fig. 4, which also shows the measured response together with the calculated values of the signal BPF. The insertion loss is 0.4 dB, including the microstrip line loss of 0.3 dB, and the attenuation in the image frequency range of 19.8–20.3 GHz is more than 45 dB. The difference between the calculated and measured curves in the lower stopband mainly resulted from the direct coupling between the input and output microstrips.

As for the local BPF, the DR is tightly coupled to the lines for sufficient injection of the local output power into the mixer diode.

The IF signal through the IF LPF is fed into the IF amplifier constructed on the underside of the substrate via the hole in the substrate. The measured conversion loss for a intermediate frequency range of 1.1–1.6 GHz is shown in Fig. 5. A conversion loss of less than 6.5 dB is obtained over the 500 MHz bandwidth.

V. Local Oscillator

The local oscillator for the front end of the home receiver requires high frequency stability, low phase noise, and low power consumption. In order to meet these requirements, a dielectric resonator oscillator (DRO) was selected. The DRO uses a single GaAs FET and a DR as shown in Fig. 6(a). An equivalent circuit of the oscillator is shown in Fig. 6(b). The DRO circuit is similar to those reported in the lower frequency range [15], [16]. In design-

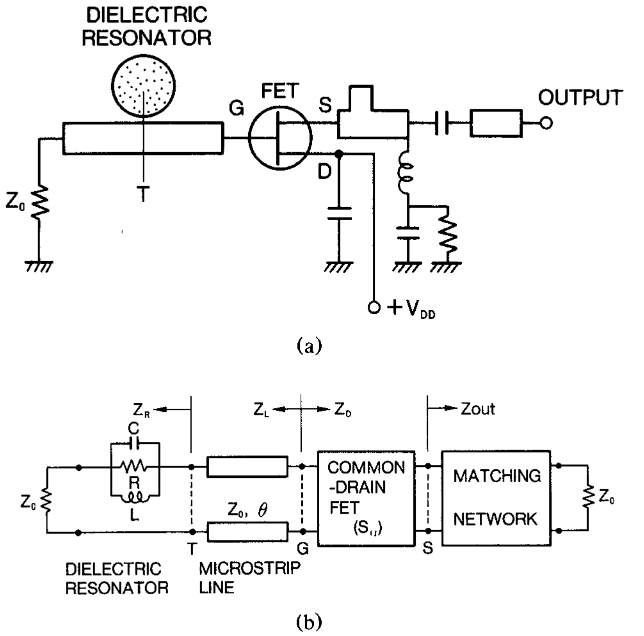


Fig. 6. (a) Construction of local oscillator. (b) Equivalent circuit of local oscillator.

ing the oscillator, particular attention was paid to the mounting structure of the DR to realize a high Q factor and to the large-signal S parameters of the FET necessary to derive the relationship between the Q's of the DR and the output power.

A. Considerations for High-Q DR Filter

Fig. 7(a) shows a cross-sectional view of the mounting structure of the high-Q DR filter. The DR is magnetically coupled to a microstrip line. To stabilize the oscillator, the resonant mode is cylindrical $TE_{01\delta}$. The DR is composed of $Ba(Mg_{1/3}Ta_{2/3})O_3$ ceramics [11] with a relative dielectric constant of 24, and is mounted on the support rod with epoxy adhesive. On the side of the DR, there is no alumina to separate spurious modes from the desired $TE_{01\delta}$ mode and to reduce the deterioration of the unloaded Q factor. The definitions of Q's are found in Fig. 7(b), where Q_0, Q_E, and Q_L denote the unloaded Q, external Q, and loaded Q, respectively.

By employing the structure shown in Fig. 6(a), a Q_0 of approximately 5500 is obtained. The Q_L of this DR filter varies as a function of the distance d between the microstrip line and the DR. As shown in Fig. 7(c), the Q_L increases from 550 for a d of -0.1 mm to 1500 for a d of 0.4 mm.

B. Design of Highly Stabilized Oscillator

The oscillator shown in Fig. 6 is designed based on the measured small-signal common-source S parameters of the FET. The device was a GaAs FET chip (NE67300, NEC) with a $0.3\times280\ \mu m^2$ gate, and measurements were carried out at $V_{DS}=3.0$ V, $I_{DS}=25$ mA, and $f=21.4$

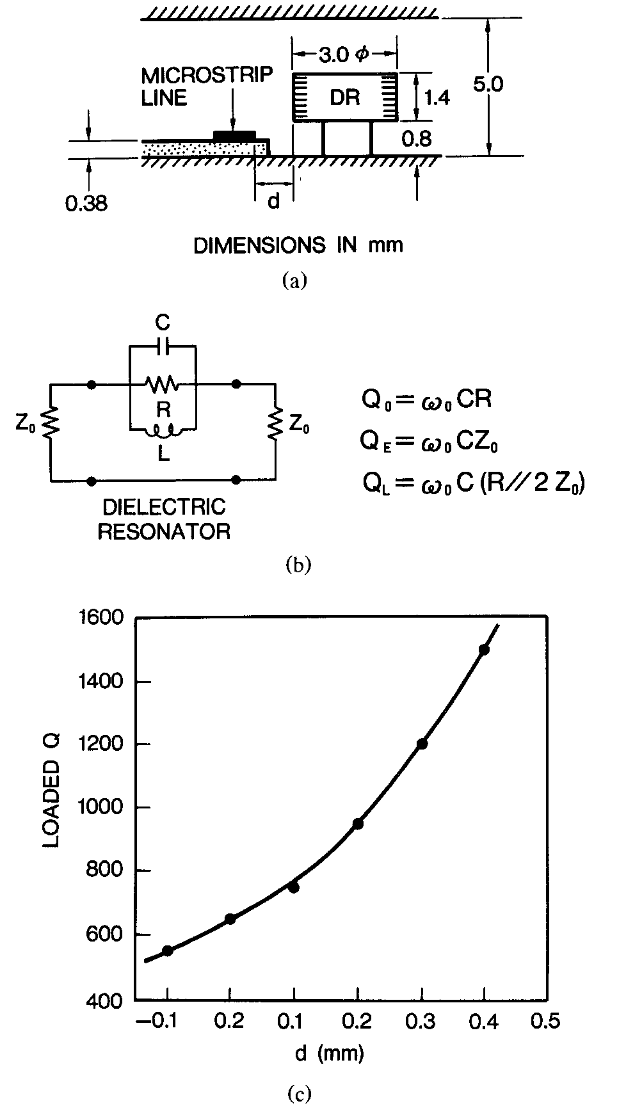


Fig. 7. (a) Cross-sectional view of dielectric resonator filter. (b) Definitions of Q's. (c) Loaded Q of dielectric resonator filter.

GHz. The measured common-source S parameters are listed below:

$$S_{11}=0.63\angle-151^\circ \qquad S_{12}=0.12\angle37^\circ$$
$$S_{21}=1.4\angle44^\circ \qquad S_{22}=0.57\angle-75^\circ.$$

Using common-drain y parameters converted from the above data, the device impedance Z_D seen from terminal G in the equivalent circuit of the oscillator shown in Fig. 6(b) is represented as

$$Z_D=\frac{1+Y_{22}Z_{out}}{Y_{11}+(Y_{11}Y_{22}-Y_{12}Y_{21})Z_{out}} \tag{1}$$

and the oscillating condition is determined by

$$Z_D+Z_L=0. \tag{2}$$

From (1) and (2), the combination of the output impedance, Z_{out}, and the device impedance, Z_D, is opti-

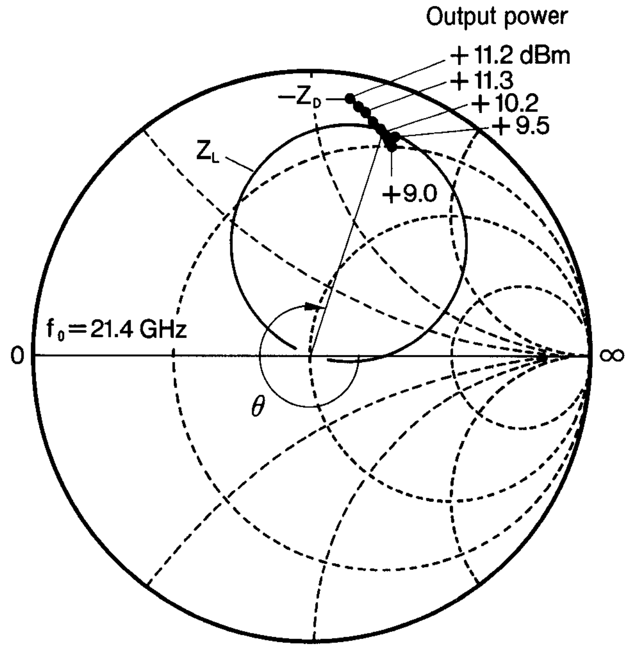


Fig. 8. Relationship between device line ($-Z_D$) and load line (Z_L).

mized for the maximum negative resistance of Z_D. The optimum combination of Z_{out} and Z_D is obtained as follows:

$$Z_{out} = 175.1 + j71.3\ (\Omega) \qquad Z_D = -19.0 - j70.9\ (\Omega).$$

A matching network is designed to realize the above Z_{out}.

To predict the output power of the oscillator when the Q's of the DR are given, the large-signal characteristics of an FET with the matching network are needed. The impedance Z_D seen from the reference plane G in Fig. 6(b) was measured. When the output power is less than +9.0 dBm, the measured Z_D is constant and coincides with the calculated value.

Fig. 8 shows the device line $-Z_D$ on a Smith chart as a function of an output power of more than +9.0 dBm. There exists the optimum impedance Z_D for the oscillator to generate the maximum output power. On the other hand, the load line Z_L (the impedance locus of the DR filter seen from the same reference plane) depends on both the Q_0 and the Q_L of the filter. For a given Q_0, the diameter of the load line circle increases with an increasing Q_L. The output power of the oscillator is given at the intersection of the device line and the load line. For the maximum oscillating power, the load line must cross the device line at the power optimum impedance. To satisfy this condition, the optimum Q_L value exists for the given Q_0. $Q_L = 700$ is the value for $Q_0 = 5500$. When Q_L is increased to achieve high frequency stability and low phase noise of oscillation, output power decreases. The load line in Fig. 8 where $Q_0 = 5500$ and $Q_L = 1200$ is obtained from the previous experiment. From Fig. 8, the oscillator output power is predicted to be +10.2 dBm, which is slightly lower than the maximum power of +11.3 dBm.

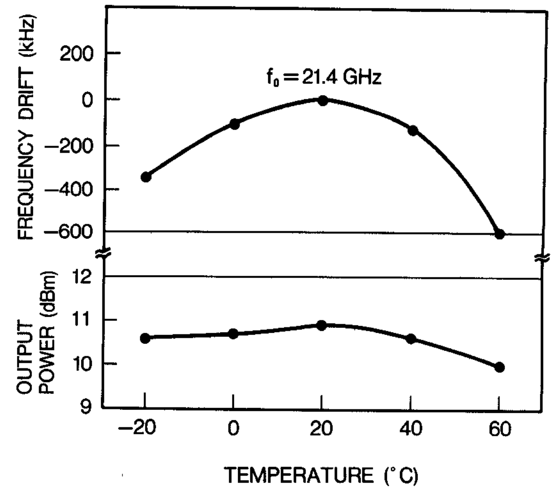


Fig. 9. Temperature dependences of oscillation frequency and output power.

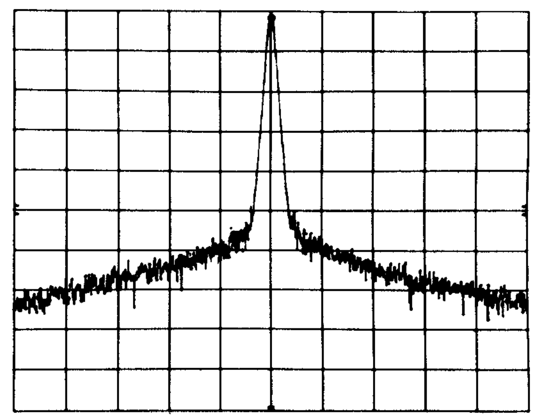


Fig. 10. Output spectrum of local oscillator. Center frequency is 21.4 GHz. Res. BW = 1 kHz. Hor. div. = 10 kHz. Vert. div. = 10 dB.

C. Performance of Local Oscillator

The 21.4 GHz local oscillator circuit is fabricated in a brass housing. The temperature coefficient of the resonant frequency of the DR is +0.7 ppm/deg. The experimental results of the temperature dependences of the oscillation frequency and output power of the local oscillator are shown in Fig. 9. The local oscillator has achieved a frequency drift of less than 600 $\text{kHz}_{\text{p-p}}$ and an output power variation of less than 1 $\text{dB}_{\text{p-p}}$ with an output power of more than 10 dBm over a temperature range of −20°C to +60°C.

As shown in Fig. 10, the output spectrum of the oscillator has a phase noise of −89 dBc/Hz at 10 kHz off from the carrier when the Q_L of the DR is 1200. No spurious oscillation was observed.

VI. Total Performance of 22-GHz-Band Down-Converter

The components described above were integrated into a down-converter. An internal view of a trial 22 GHz band down-converter is shown in Fig. 11. The IFA is located on the underside of the mixer and local oscillator.

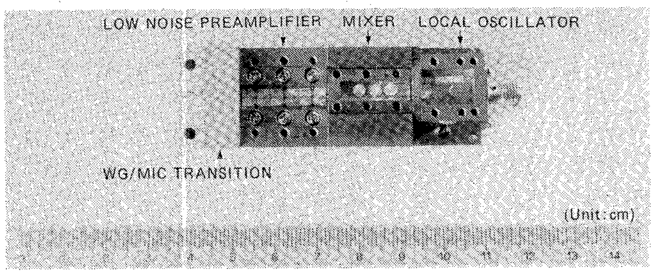


Fig. 11. Internal view of trial 22-GHz-band low-noise down-converter.

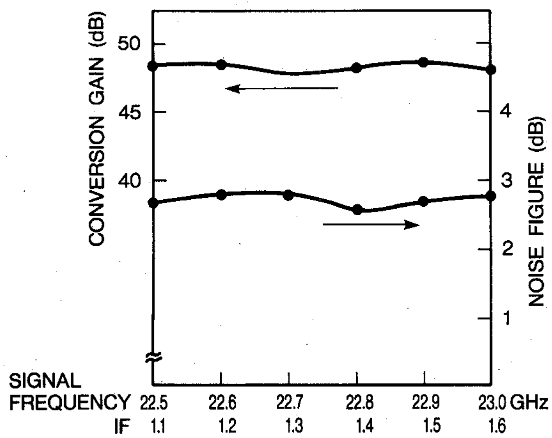


Fig. 12. Total noise figure and conversion gain of 22-GHz-band down-converter.

TABLE I
EXAMPLE OF LINK BUDGET IN THE 22 GHz BAND

Channel Bandwidth	(MHz)	75	
TWT power	(dBW)	23	200 W
Feeder loss	(dB)	−2.0	
Transmitting antenna gain	(dB)	46.5	Beam size of 0.6°
Pointing loss	(dB)	−0.5	
Free space loss	(dB)	−211.5	
Rain attenuation	(dB)	−9.5	99% of time
Receiving antenna gain	(dB)	43.5	0.75 m$^{\phi}$ 70%
Noise temperature	(K)	530*	NF = 2.8 dB
Total C/N	(dB)	12.1	C = −110.5 N = −122.6

*including atmospheric noise 265 K.

The connection between the mixer and IFA is made with a coaxial feed through pins in the wall between the two chambers. The dc bias circuits for the LNA and LO are installed on the underside of the LNA. The voltage of the dc power supply is 15 V, and the total power consumption is 2.5 W. The dimensions of the converter are $28 \times 28 \times 80$ mm^3.

A total noise figure of less than 2.8 dB and a conversion gain of more than 48 dB are obtained over the 22.5–23.0 GHz frequency range, as shown in Fig. 12. Table I shows an example of the link budget for satellite broadcasting. Total C/N satisfies the required C/N of 11.8 dB for the digital service proposed by our laboratory [17].

With this converter, an FM HDTV signal was successfully received in a terrestrial transmission test.

VII. Conclusion

A low-cost, low-noise 22 GHz band down-converter for satellite broadcast receivers has been developed using MIC technology. An inexpensive LNA is realized with low-cost HEMT's for a 12 GHz band DBS down-converter. A simple and novel mixer with DR filters has been constructed. The local oscillator with high-Q DR configuration exhibits low frequency drift and low phase noise.

An overall noise figure of 2.6–2.8 dB throughout the 22.5–23.0 GHz band and an LO frequency drift of 600 kHz$_{\text{p-p}}$ over a −20°C to +60°C temperature range was obtained. The cost of this converter is estimated to be equal to or less than that of a 12 GHz band DBS down-converter. The experimental results obtained here will contribute to system design for future 22 GHz band satellite broadcasting. This converter is expected to be one of the best candidates for home receivers in the 22 GHz band.

Acknowledgment

The authors would like to thank Dr. K. Yamamoto, Dr. Y. Utsumi, and N. Yazawa for their encouragement and helpful discussions.

References

[1] H. Ogawa, K. Yamamoto, and N. Imai, "A 26-GHz high-performance MIC transmitter/receiver for digital radio subscriber systems," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1551–1556, Dec. 1984.

[2] P. G. Wilson and B. C. Barnes, "Millimeter-wave downconverter using monolithic technology for high volume application," in *Proc.* 1989 *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1099–1102.

[3] L. C. T. Liu, C. S. Liu, J. R. Kessler, S.-K. Wang, and C.-D. Change, "A 30-GHz monolithic receiver," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1548–1552, Dec. 1986.

[4] M. Muraguchi, T. Hirota, A. Minakawa, K. Ohwada, and T. Sugeta, "Uniplanar MMIC's and their applications," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1896–1901, Dec. 1988.

[5] T. Kasuga *et al.*, "Cryogenically cooled *K*-band high electron mobility transistor receiver for radio astronomical observation," *Rev. Sci. Instr.*, vol. 58, pp. 379–382, 1987.

[6] D. E. Meharry, J. L. Bugeau, W. J. Coughlin, and M. A. Priolo, "6 to 18 GHz transmit/receive modules for multifunction phased arrays," in *Proc.* 1989 *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 115–118.

[7] Y. Utsumi and K. Imai, "22 GHz band low noise down converter for satellite broadcasting," *IEEE Trans. Broadcast.*, vol. BC-30, pp. 1–7, Mar. 1984.

[8] Y. Sasaki, K. Nagahama, K. Hosono, T. Katoh, and M. Komaru, "A high electron mobility transistor with a mushroom gate fabricated by focused ion beam lithography," in *Proc.* 1988 *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 251–254.

[9] K. H. G. Duh *et al.*, "High-performance Ka-band and V-band HEMT amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1598–1603, Dec. 1988.

[10] S. Kawasima, N. Nishida, I. Ueda, and H. Ouchi, "Dielectric properties of $Ba(Zn_{1/3}Nb_{2/3})O_3 - Ba(Zn_{1/3}Ta_{2/3})O_3$ ceramics at microwave frequency," MW80-29, IECE Japan, pp. 1–4, Sept. 1980.

[11] K. Matsumoto, T. Hiuga, K. Takada, and H. Ichimura, "$Ba(Mg_{1/3}Ta_{2/3})O_3$ ceramics with ultra-low loss at microwave frequencies," in *Proc. 6th IEEE Int. Symp. Applications Ferroelectrics*, 1986, pp. 118–121.

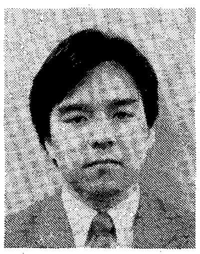
[12] K. Imai and H. Nakakita, "A 22 GHz band low noise down converter for satellite broadcast receivers," in *Proc. 19th European Microwave Conf.*, Sept. 1989, pp. 549–554.

[13] H. Ishiuchi *et al.*, "Super low noise hetero-junction FET," *NEC Tech. J.*, vol. 40, no. 5, pp. 37–39, May 1987.
[14] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures.* New York: McGraw-Hill, 1964.
[15] A. Podcameni and L. A. Bermudez, "Stabilised FET oscillator with input dielectric resonator: Large signal design," *Electron. Lett.*, vol. 17, pp. 44–45, Jan. 1981.
[16] C. Tsironis, "Highly stable dielectric resonator FET oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 310–314, Apr. 1985.
[17] K. Kameda and T. Yamamoto, "A study on satellite broadcasting service in the 22 GHz band," in *Proc 17th Int. Symp. Space Technology and Science*, 1990, pp. 1691–1700.

Kazuo Imai was born in Yokohama, Japan, on April 13, 1950. He received the B.E. and M.E. degrees in electronic engineering from Waseda University, Tokyo, Japan, in 1975 and 1977, respectively.

He joined NHK (Japan Broadcasting Corporation), Tokyo, in 1977. Since 1980, he has worked at their Science and Technical Research Laboratories, where he has been engaged in research and development work on microwave and millimeter-wave circuits and in the analysis and design of low-noise receivers for satellite broadcasting.

Mr. Imai is a member of IEICEJ (Institute of Electronics, Information and Communication Engineers of Japan) and ITEJ (Institute of Television Engineers of Japan).



Hisao Nakakita was born in Osaka, Japan, on June 14, 1959. He received the B.E. degree in electrical and communication engineering from Osaka University, Osaka, Japan, in 1982.

In 1982, he joined NHK (Japan Broadcasting Corporation) and worked at the Matsuyama broadcasting station. Since 1986, he has been engaged in research on microwave and millimeter-wave circuits and in the development of low-noise receivers for 22-GHz- and 42-GHz-band broadcasting at the science and Technical Research Laboratories of NHK.

Mr. Nakakita is a member of the Institute of Electronics, Information and Communication Engineers of Japan.