Stripline Dual-Mode Ring Resonators and Their Application to Microwave Devices

Hiroyuki Yabuki, Morikazu Sagawa, *Member, IEEE*, Michiaki Matsuo, and Mitsuo Makimoto, *Member, IEEE*

***Abstract*—This paper describes the fundamental properties of two orthogonal resonant modes within stripline ring resonators and their application to microwave devices. There are two principal methods for application of ring resonators, the first is by using two-port devices and the second four-port devices. In the case of two-port configurations, dual-mode filters using coupling between two degenerate modes have been studied as typical applications. In this paper, new methods for the coupling of two modes and their applications to practical devices are proposed, and then experimental results for proof of the new structures are presented. Four-port configurations, which make use of two resonant modes as being independent or having no coupling between them, have a wider range of application to microwave devices. Microwave circuits such as tuned amplifiers and oscillators with novel structures are proposed, and their excellent characteristics are demonstrated. The experimental results obtained in this study on two and four-port devices make it clear that dual-mode ring resonators have great potential for application to various microwave devices.**

I. Introduction

It is well known that ring resonators have low radiation losses, high Q values, and two orthogonal resonant modes (dual-mode) [1]. Filters and duplexers using dual-mode dielectric resonators or waveguide ring cavities have been used for satellite communications [2]. Some applications which make use of the dual-mode in a stripline [3]–[5] and a slotline [6] configuration are also reported. The authors have previously reported the fundamental properties of one wavelength dual-mode resonators, including the exciting means, and methods of coupling control between two degenerate modes [7]. We have also proposed their application to filtering and oscillating devices [8].

Two different methods are used for the application of dual-mode ring resonators. The first method, making use of the coupling between two orthogonal resonant modes, is adopted for two-port devices. In the second method, two independent modes are used and applied to four-port devices.

This paper investigates two types of dual-mode ring resonators (DMR's) with two and four-port configurations. Two-port configurations have previously been reported as dual-mode filters using the coupling between two orthogonal modes in the resonators. In this paper, various coupling methods between two modes are indicated, and the simulated and trial results of dual-mode filters with practical structures are then described. In the case of the four-port configuration, some features such as methods for miniaturization and isolation characteristics between two modes are presented. Design examples and performances of microwave devices such as tuned amplifiers, oscipliers (oscillators having multiplier function), and low phase noise voltage controlled oscillators (VCO's) are also demonstrated for verification of the above mentioned features.

Manuscript received August 31, 1995; revised January 17, 1996.

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Publisher Item Identifier S 0018-9480(96)03036-0.

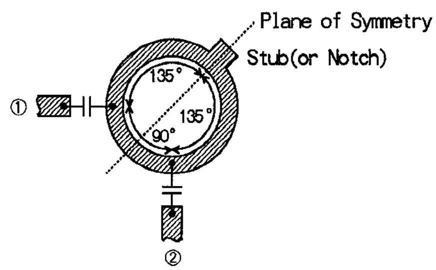

Fig. 1. Basic structure of a dual-mode filter using a stripline ring resonator.

II. Two-Port Devices Using One Wavelength Ring Resonators

A. Coupling Methods of Two Orthogonal Resonant Modes

Fig. 1 shows a basic structure of the dual-mode filter using coupling between two orthogonal modes within the ring resonator. Input and output ports are spatially separated 90 degrees from each other and perturbations such as a stub or a notch are introduced within the resonator at a location that is offset 135 degrees from input and output ports. When no perturbations exist within the resonator, port 2 generates no response even if port 1 is excited at the resonance frequency. The presence of perturbations results in a response being elicited. The coupling between two orthogonal modes can be accomplished by introducing the perturbation within the resonator.

General conditions to form dual-mode filters using one wavelength ring resonators are as follows:

1) The input and output ports should be spatially separated 90 degrees from each other.
2) A discontinuity or some means of generating reflected waves against incident waves, should exist within the resonator.
3) A plane of symmetry should exist in the circuit geometry.

Some structures shown in Fig. 2 can also be excited in two orthogonal modes, forming dual-mode filters such as that outlined in Fig. 1. Fig. 2(a) shows a structure which possesses

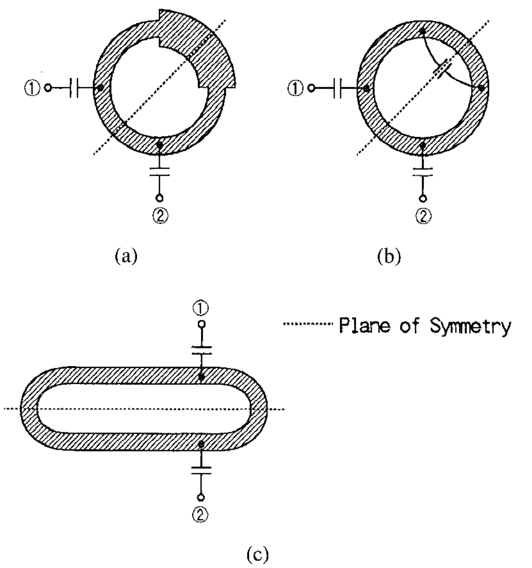

Fig. 2. Some structural variations of stripline dual-mode filters. (a) Structure having an impedance step. (b) Structure having a lumped element component. (c) Structure having parallel coupled lines.

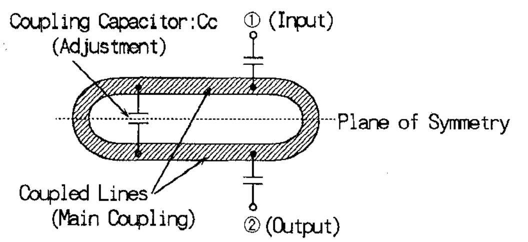

Fig. 3. Practical realization of a stripline dual-mode filter.

an impedance step in a transmission line of the resonator [5], [7]. The coupling coefficient between the two modes, that is the bandwidth of the filters, can be controlled by the impedance ratio of the stepped striplines. Fig. 2(b) is one example of structures having a lumped element component, a capacitor or an inductor, parallel to the DMR transmission line. Fig. 2(c) indicates a structure using parallel coupled lines. Fig. 2(a) and (b) are examples which have a discontinuity in the specified part of the resonator and generate reflected waves. Fig. 2(c) is a structure which excites two different directional waves by parallel coupled lines. This structure is practically useful due to its compact size.

Some structural variations of dual-mode filters have been discussed above, combinations of these structures may also be employed.

B. Practical Structures for Dual-Mode Filters and Their Simulation Results

Fig. 3 represents a novel structure for compact and practical dual-mode filters. The coupled lines together with a lumped element capacitor, a combination of the methods shown in Fig. 2(b) and (c), are used for both small size and fine adjustment of bandwidth.

Fig. 4 shows the calculation results of such a dual-mode filter with the coupling capacitor C_c using a general purpose microwave simulator, such as super compact®, when the center frequency = 1.9 GHz, $Z_{0e} = 51.6\ \Omega$, and $Z_{0o} = 48.4\ \Omega$ for the parallel coupled lines. The substrate has a dielectric constant $\epsilon_r = 10.5$, thickness $h = 1.27$ mm, copper resistivity $\rho = 1.673\ \Omega$cm, and loss tangent $\tan\delta = 0.002$.

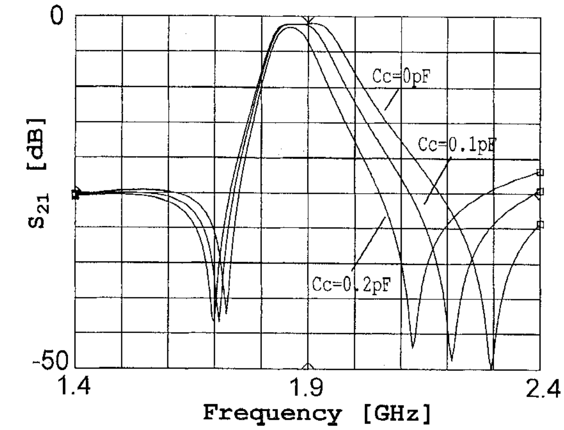

Fig. 4. Simulated performances of a two-port dual-mode filter.

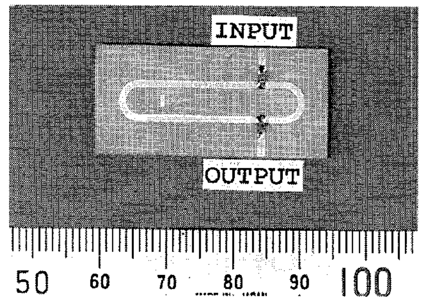

Fig. 5. A photograph of the trial filter.

C. The Experimental Dual-Mode Filter and Its Performance

On the basis of the above discussion, a dual-mode filter was designed and fabricated. Figs. 5 and 6 illustrate a photograph of the experimental filter and its measured performance, respectively. The coupling coefficient of parallel coupled lines is extremely small and easily affected by the housing. The bandwidth of the filter is, therefore, adjusted by changing the value of the coupling capacitor C_c. Passband insertion losses less than 1.3 dB were obtained. Attenuation levels of more than 20 dB at 130 MHz below and 200 MHz above the center frequency were obtained. Measured data were in good agreement with the simulation results as shown in Figs. 4 and 6.

III. Four-Port Devices Using Conventional and Miniaturized Ring Resonators

A. Special Features of Ring Resonators with Four Ports

Two-port ring resonators are applied to filtering devices using the coupling between two modes, however, two orthogonal modes uncoupled from each other are used in the case of four-port devices.

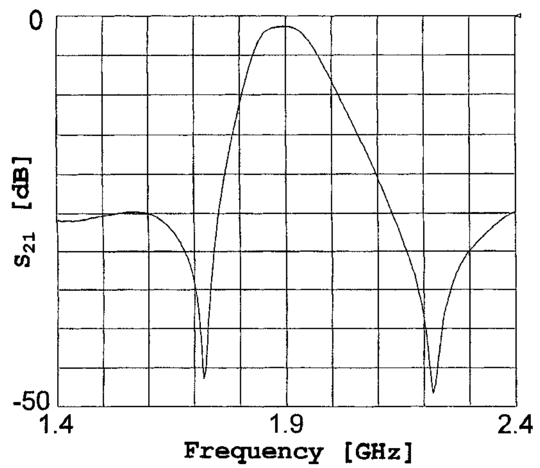

Fig. 6. Experimental results of the trial filter.

When two orthogonal modes are used:

1) The total length of ring resonators may be less than one wavelength.
2) The resonant frequencies of two orthogonal modes may be tuned independently.
   (Two different resonance frequencies may be excited.)
3) Various functional devices can be designed with a combination of active circuits.

Four-port devices are promising as resonant or reactive elements in the microwave region with many advantages as mentioned above.

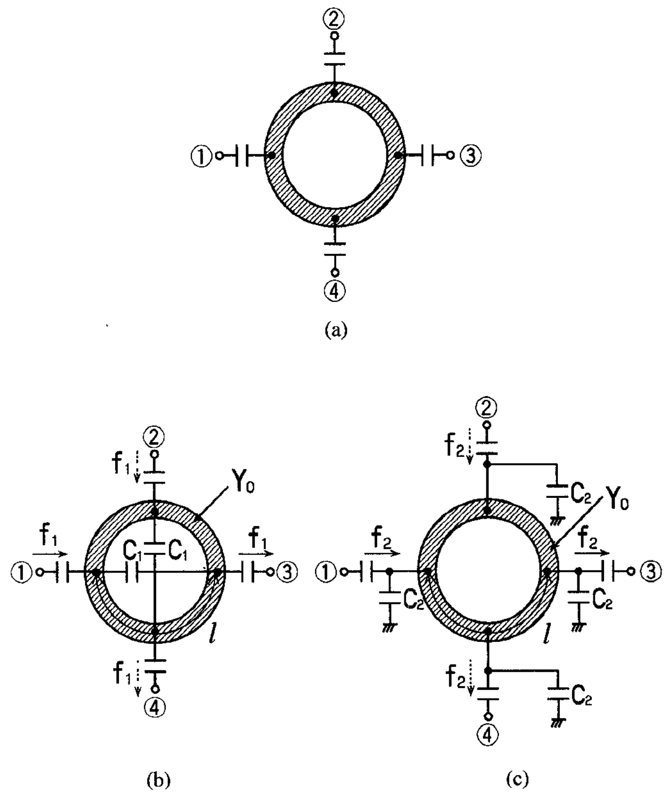

Fig. 7. Some structural variations of four-port stripline DMR's: (a) One wavelength DMR. (b) Miniaturized DMR connecting a capacitor between opposite ports. (c) Miniaturized DMR with every port grounded by a capacitor.

B. Miniaturization Methods and Isolation Characteristics Between Two Orthogonal Resonant Modes

Fig. 7 shows some structures of four-port stripline ring resonators. Fig. 7(a) is the basic structure of a one wavelength DMR. By arranging four ports whose interval is one quarter of the resonator length, two orthogonal modes can be independently excited in the ring resonator. One mode propagates from port 1 to port 3 and the other independently from port 2 to port 4 at the same frequency. One wavelength DMR's can be miniaturized by adding a capacitive element to the resonator at the high electric field points. Two methods are useful for achieving small-sized DMR's. One method is to connect a capacitor between opposite ports as shown in Fig. 7(b) and the other is to ground every port using a capacitor as shown in Fig. 7(c).

The resonance condition of the miniaturized DMR's indicated in Fig. 7(b) and (c) can be obtained by theoretical analysis using the ABCD matrix of each element. The results are as follows:

(b) type: $Y_0 \sin\theta_{01} + \omega C_1(\cos\theta_{01} - 1) = 0.$

(c) type: $(4Y_0^2 - \omega^2 C_2^2)\sin\theta_{02} + 4Y_0\omega C_2 \cos\theta_{02} = 0$

where

$$\theta_{01} = 2\pi l f_1/v_p, \quad \theta_{02} = 2\pi l f_2/v_p.$$

In the above equations, Y_0 is the characteristic admittance of the transmission line consisting of DMR's, v_p is the phase velocity on the substrates, and f_1 and f_2 represent the resonance frequencies of Fig. 7(b) and (c), respectively.

The voltage distribution exhibits sinusoidal properties along the transmission line when port 1 is excited at the resonance frequency. Port 2 and port 4 become minimum voltage points and port 3 becomes a maximum voltage point. The same behavior occurs if port 2 is excited at the resonance frequency. Therefore, two ports whose physical distance is one quarter of the resonator length are spatially orthogonal at the resonance frequency, and thus electrically isolated from each other.

Isolation characteristics are important factors to consider in microwave devices using DMR's. High isolation characteristics make it possible to fabricate filters with good attenuation performance and oscillating circuits without mutual interaction. This feature can be applied to tuned amplifiers and VCO's with wide frequency ranges. In addition, high isolation characteristics between fundamental and even order harmonics make it possible to extract even order harmonics while suppressing a fundamental frequency signal. This feature is useful for oscipliers, oscillators having a multiplier function.

Fig. 8 indicates calculation results of isolation characteristics due to the miniaturization of DMR's. Here, isolation characteristics are defined (S_{21}/S_{31}) as the selective ratio between isolation ports and transmission ports. θ_T is the total electrical length of a DMR at the resonance frequency. In the case of the Fig. 7(b) type, isolation characteristics degrade with increasing miniaturization. However, the Fig. 7(c) type maintains excellent isolation characteristics, making them preferable for oscillating devices. The Fig. 7(c) type is used in the following examination of oscillators.

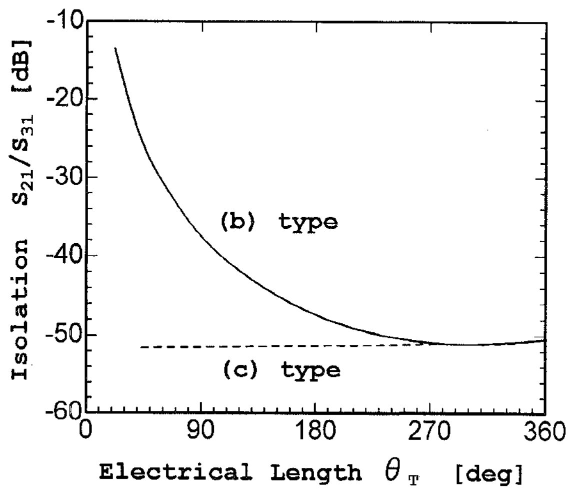

Fig. 8. Isolation characteristics of four-port DMR's.

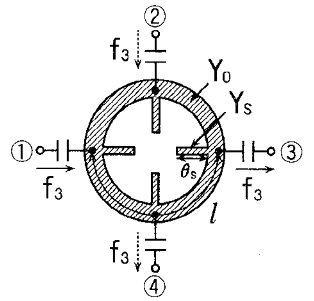

Fig. 9. A four-port DMR with open-ended stubs.

For MIC applications, it is preferable to replace the capacitor C_2 indicated in Fig. 7(c) with an open-ended stub as shown in Fig. 9. The resonance condition of the miniaturized DMR's with open-ended stubs is as follows:

$$4Y_0Y_s\tan\theta_s + 4Y_0^2\tan\theta_{03} - Y_s^2\tan^2\theta_s\tan\theta_{03} = 0.$$

where

Y_s: the characteristic admittance of open-ended stubs,
θ_s: electrical length of open-ended stubs,
θ_{03} $= 2\pi l f_3/v_p$,
f_3: the resonance frequency of the DMR shown in Fig. 9.

C. Examples of Practical Applications and Experimental Results

On the basis of above discussion and making use of the special features of DMR's, the following tuned amplifier and two types of oscillating circuits were designed and fabricated.

Tuned Amplifier: Fig. 10 shows a basic configuration of the tuned amplifier using the DMR. The tuned amplifier consists of three sections, a prefilter, an amplifier and a postfilter. The two filters are made as one DMR. To maintain high isolation characteristics between two orthogonal modes, a dual-gate GaAs MESFET, second gate RF grounded, is used as the amplifier element. This amplifier must have excellent unilateral performance. The matching circuits between the filter and the amplifier are made compact by employing only

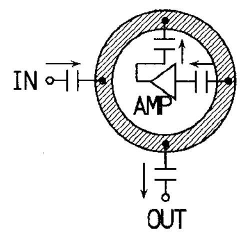

Fig. 10. Basic configuration of a tuned amplifier.

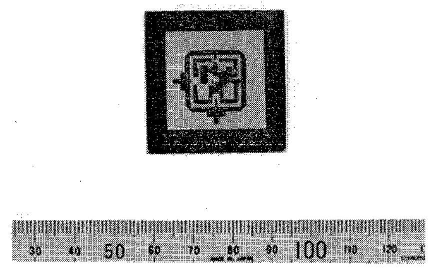

Fig. 11. A photograph of the experimental tuned amplifier.

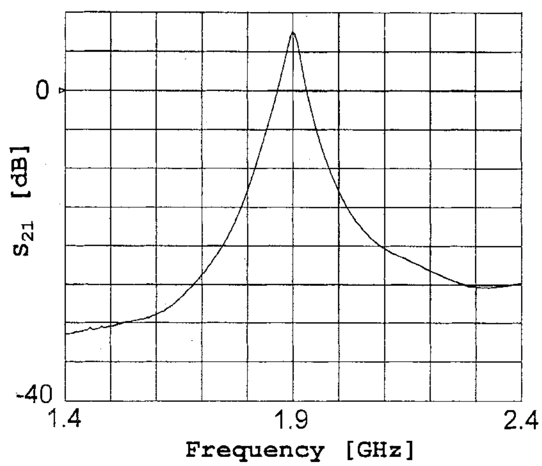

Fig. 12. Experimental results of the experimental tuned amplifier.

input and output coupling using the impedance conversion characteristics of the coupling capacitors. The amplifier can be also placed inside the DMR for compactness. Figs. 11 and 12 illustrate a photograph and the experimental results of the tuned amplifier, respectively. The total gain is about 7.5 dB and the noise figure is approximately 3.5 dB at the center frequency of 1.9 GHz. The 3 dB passband width is about 30 MHz. These results show that these circuits are suitable for narrow band applications.

Low Phase Noise VCO's: Ring resonators are often used as the reactive elements of low phase noise oscillators because of these high Q values and steep susceptance gradients. It is known that the phase noise characteristics of VCO's degrade remarkably with widening frequency range. This problem can be solved by using the DMR as a resonator. Two VCO's using a DMR can operate independently in a frequency range in which the isolation exceeds the injection locked gain. The injection locked gain is defined as the ratio of the oscillator

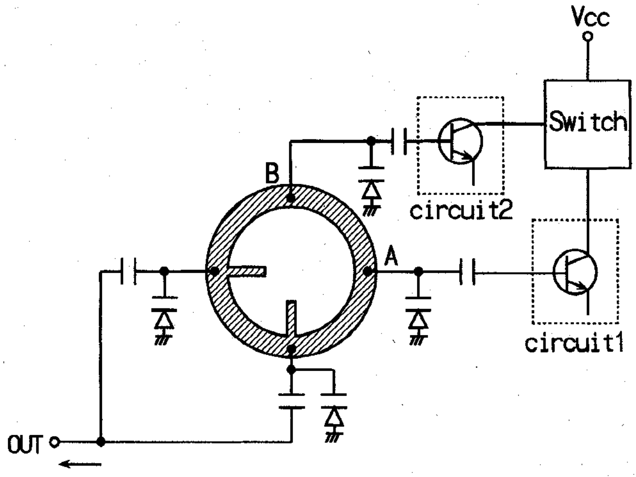

Fig. 13. Circuit configuration of a low phase noise VCO.

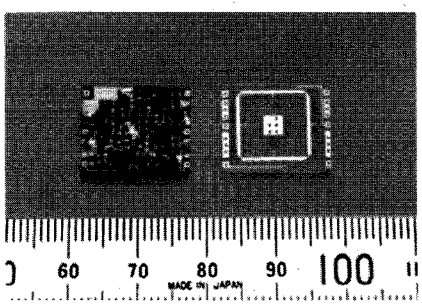

Fig. 14. A photograph of the experimental low phase noise VCO.

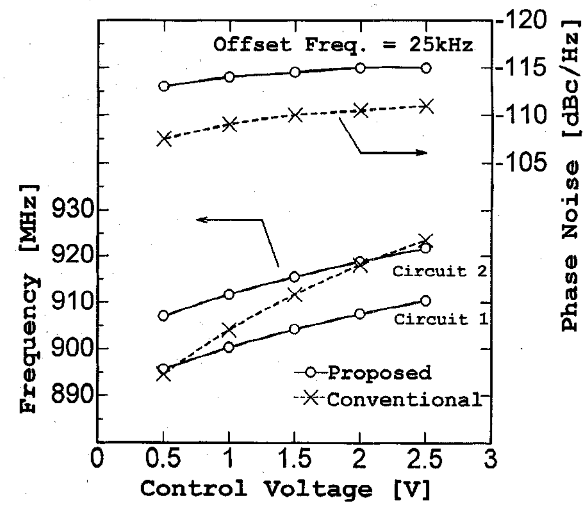

Fig. 15. Comparison between the characteristics of a conventional and the proposed VCO's.

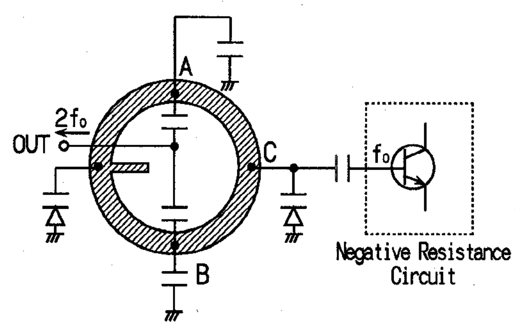

Fig. 16. Circuit configuration of an oscíplier.

output level to the injection locking input level at the same port. The experimental results make it clear that the two oscillators are independent of each other when the difference frequency of the oscillators is more than 5 MHz.

Fig. 13 shows a circuit configuration of the trial VCO's. Circuit 1 covers the lower, while circuit 2 covers the higher frequency band ranges. The alternative circuit operates by the switch. Both oscillators are composed of a common DMR and two identical negative resistance circuits. The introduction of this method reduces the variable frequency range of VCO's to about one half of the conventional one. As a result, the phase noise characteristics of the oscillators are significantly improved.

Fig. 14 illustrates a photograph of the experimental low phase noise VCO. This circuit is constructed from a four-layer printed circuit board. Fig. 15 shows a comparison between the conventional and the proposed VCO's concerning the oscillation frequency and SSB phase noise versus the control voltages. The phase noise characteristics of the proposed VCO are superior to those of the conventional one with approximately 5 dB improvement within the operating range. Making use of isolation properties of the DMR, the experimental VCO incorporating the DMR is able to realize low phase noise characteristics as a result of their low sensitivity versus control voltages.

Oscíplier: DMR's have special structures for obtaining outputs at the fundamental oscillating frequency f_0 and its second harmonic frequency $2f_0$, separately, with high isolation between them.

Fig. 16 shows a circuit configuration of the oscíplier using a miniaturized DMR. Points A and B, whose distances from point C are one quarter of the total DMR length, become minimum voltage points at a resonance frequency of f_0. However, the maximum voltage cannot be obtained at $2f_0$. To make point A and B maximum voltage points at $2f_0$, it is necessary to connect capacitors from the output ports to the ground. Even in this situation, the f_0 signal is not affected because these points are short-circuited points at f_0. The phase difference between A and B becomes 180° at the f_0 signal and is in-phase at the $2f_0$ signal. The oscíplier can be produced by the in-phase combination of the two outputs of A and B, with its fundamental frequency suppressed and second harmonic frequency emphasized.

Next, we study voltage controlled oscípliers. Maximum isolation points, whose output level is a minimum at f_0 and a maximum at $2f_0$, vary in proportion to oscillation frequency when a varactor diode is connected to one side of the ports. However, the maximum isolation points are fixed when varactor diodes are connected to both sides of the ports, as shown in Fig. 16.

Fig. 17 shows a photograph of the experimental voltage controlled oscíplier. This circuit is also manufactured on a four-layer printed circuit board. Figs. 18 and 19 show the

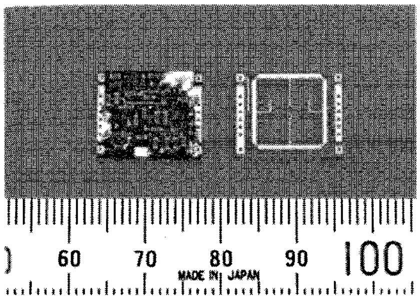

Fig. 17. A photograph of the experimental osciplier.

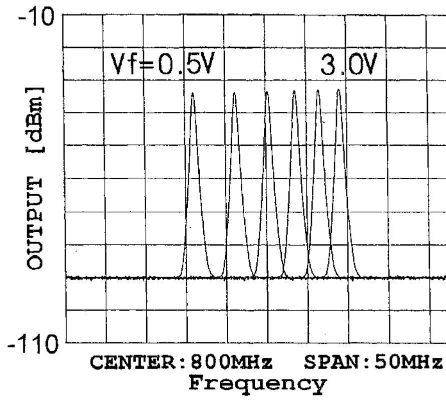

Fig. 18. Experimental results of the osciplier. (f_0 output)

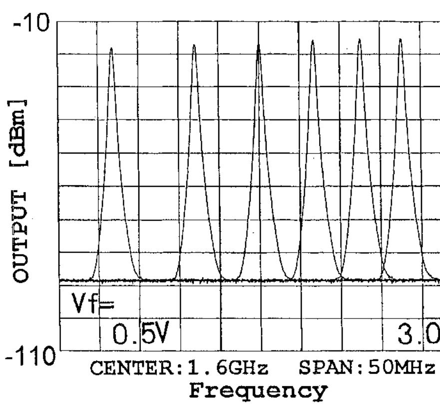

Fig. 19. Experimental results of the osciplier. ($2f_0$ output)

experimental results of the osciplier for the f_0 and $2f_0$ output spectrum, respectively. The output frequency f_0 is about 800 MHz. Both output levels are constant and the fundamental suppression level is about 18 dB in a control voltage range from 0.5 V to 3.0 V. Osciplers using the DMR are expected to operate at a high frequency with low power consumption as a result of not requiring multipliers.

IV. Conclusion

New methods for coupling between two orthogonal modes are proposed to apply to two-port devices. The experimental results of dual-mode filters using the new methods proved that useful filters having a compact size and a fine adjustment function of bandwidth can be designed.

Microwave circuits such as tuned amplifiers and two types of oscillators have been developed as four-port devices which use two orthogonal modes. These circuits include the miniaturized DMR's with lumped or distributed elements whose resonance conditions are analytically derived. These newly developed circuits are remarkably useful and practical for creating low-profile, low power consumption and low phase noise characteristics. DMR's have several attractive features which are useful for microwave devices, and they are expected to have a practical use for various kinds of radio equipment in the RF and microwave regions. In addition, these basic circuit configurations and design concepts are also applicable for millimeter wave devices.

Acknowledgment

The authors wish to thank M. Kanno and S. Yamashita for their continuous encouragement.

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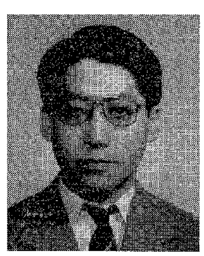

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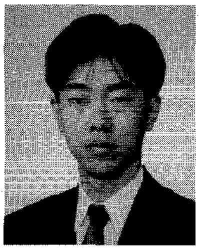

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