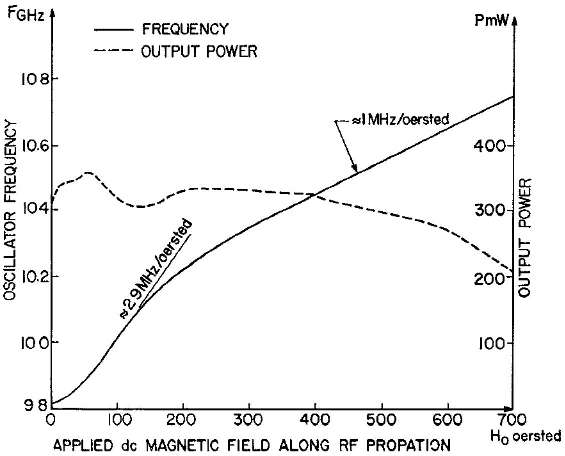

Fig. 4. Power and frequency versus applied dc magnetic field obtained with an output circuit built on a silica substrate and using a ferrite-filled resonator coupled to the diode.

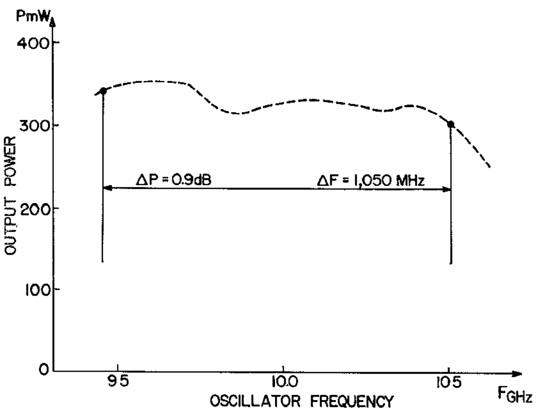

Fig. 5. Power versus frequency obtained by tuning the oscillator with a permanent magnet.

Fig. 3 shows the results obtained with the oscillator biased by an electromagnet; the magnetic field was applied in the direction of the propagation.

Fig. 4 shows similar results obtained with the 50-Ω line and quarter-wavelength transformer made on a silica substrate. The diode is coupled to the same ferrite-filled microstrip resonator as previously described.

Frequency tuning has also been achieved with a small cylindrical permanent magnet 0.500 in wide and 0.500 in long. The fringing field of the magnet has a maximum value of about 2000 Oe. Frequency tuning is obtained by sliding the magnet across the shielded end of the ferrite-filled microstrip resonator. Part of the frequency tuning, at the low end, is obtained by the transverse component of the magnetic field. Fig. 5 shows the results which have been obtained by this method.

Conclusion

A variable frequency microstrip resonator using a partially magnetized ferrite substrate has been used for tuning an X-band IMPATT oscillator. Frequency tuning with a slope of about 4.6 MHz/Oe has been achieved with a magnetic field of 30 to 80 Oe applied in the direction of the RF propagation. Frequency tuning has also been obtained by displacement of a small magnet across the shielded end of the resonator. In this way a tuning range of about 10 percent was obtained with an output power of 330 mW ±0.5 dB.

References

[1] G. E. Brehm and S. Mao, "Varactor-tuned integrated Gunn oscillators," *IEEE J. Solid-State Circuits*, vol. SC-3, pp. 217–220, Sept. 1968.
[2] R. J. Clark, Jr., and D. B. Swartz, "Combine YIG's with bulk-effect diodes," *Microwaves*, Mar. 1972.
[3] D. J. Ellis and M. W. Gunn, "YIG tuning of a stripline Gunn oscillator," *IEEE J. Solid-State Circuits* (Special Corresp.), vol. SC-7, pp. 63–65, Feb. 1972.
[4] D. Zieger, "Frequency model of a Gunn effect oscillator by magnetic tuning," *Electron. Lett.*, vol. 3, July 1967.
[5] N. S. Chang, T. Hayamizu, and Y. Matsuo, "YIG-tuned Gunn effect oscillator," *Proc. IEEE (Lett.)*, vol. 55, p. 1621, Sept. 1967.
[6] M. Omori, "Octave electronic tuning of a CW Gunn diode using a YIG sphere," *Proc. IEEE (Lett.)*, vol. 57, p. 97, Jan. 1969.
[7] H. Suhl and R. L. Walker, "Topics in guided wave propagation through gyromagnetic media," *Bell Syst. Tech. J.*, vol. 33, Sept. 1954.
[8] M. E. Brodwin, "Propagation in ferrite-filled microstrip," *IRE Trans. Microwave Theory Tech.*, vol. MTT-6, pp. 150–155, Apr. 1958.
[9] M. E. Brodwin and D. A. Miller, "Propagation of the quasi-TEM mode in ferrite-filled coaxial line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-12, pp. 496–503, Sept. 1964.
[10] E. Schlömann, "Microwave behavior of partially magnetized ferrites," *J. Appl. Phys.*, vol. 41, Jan. 1970.
[11] J. J. Green, E. Schömann, F. Sandy, and J. Saunders, "Characterization of the microwave tensor permeability of partially magnetized materials," Semiannual Rep. RADC-TR-69-93, Feb. 1969.
[12] R. A. Pucel and D. J. Massé, "Microstrip propagation on magnetic substrates—Part I: Design theory," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 304–308, May 1972.

Double-Amplification Mode Maser

S. DMITREVSKY AND P. C. KREMER

***Abstract*—A chromium-doped rutile traveling-wave maser utilizing simultaneously two signal frequency transitions has been designed and a prototype section tested.**

The use of a chromium-doped rutile as an active medium for a paramagnetic maser is governed by the following properties of the material [1].

1) The ground state of the Cr^{3+} ion is split in a magnetic field into four levels (designated 1, 2, 3, and 4, in the order of increasing energy).

2) The ion can be located in one of two magnetically inequivalent sites.

3) For a magnetic field inclined at the angle of 54°44′ ($=\cos^{-1} 1/\sqrt{3}$) to the c axis and lying in the (010) or (100) planes, the energy levels of the two sets of inequivalent ions are identical and the frequencies of the 1–2 and 3–4 transitions are equal. The lowest frequency of the 2–3 transition is 21.7 GHz.

The choice of the direction of the magnetic field specified above results in an efficient use of the active medium in that all chromium ions participate in the gain mechanism, and all four level populations contribute to the establishment of population inversion. For signal frequencies above 21.7 GHz, this can be achieved by employing the push–pull pumping scheme. For signal frequencies below 21.7 GHz, 1–2 and 3–4 are utilized as the signal and 1–4 as the pump transitions; this mode of operation has been designated the double-amplification mode [2].

Following the guidelines sketched above, a prototype test section of a 15.7 GHz traveling-wave maser has been built and tested. The high values of permittivity of rutile (250 and 150 in the directions parallel and perpendicular, respectively, to the c axis) allow one to obtain a slowing factor of about 15 by employing dominant-mode rectangular waveguides filled with rutile. The waveguide dimensions chosen were 0.07×0.14 cm². The need to eliminate gaps between metallic walls and the dielectric for structures of this size precluded the use of machined parts, and electrolytic deposition methods had to be employed.

The observed electronic gain of a 12-mm-long test section at 4.2 K was 2.5 dB with a 3-dB bandwidth of 25 G. For the low value of gain observed, the amplifier bandwidth is approximately equal to the combined linewidth of the two signal frequency transitions involved. Thus, with the incremental gyromagnetic ratio of 4.6 MHz/G, the effective value of linewidth was approximately 115 MHz. When not pumped, the electronic loss of the structure was 2.5 dB/cm at 4.2 K. Due to different filling factors of the two signal frequency transitions, the ratio of gain to loss, 2.5/2.5 dB = 1, can be equated to the inversion ratio only if one assumes the same spin temperature (negative) for the two transitions.

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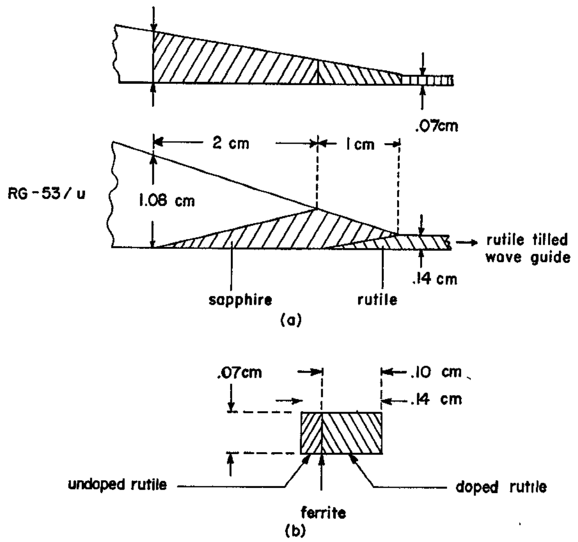

Fig. 1. (a) Coupler dimensions. (b) Isolator cross section.

TABLE I

Signal frequency			15.7 GHz		
Pump frequency			61 GHz		
Magnetic field			3.35 kG		
Operating temperature			4.2 K		
Electronic gain			2 dB/cm		
Isolator reverse/forward loss			3 dB/cm / 0.2 dB/cm		
Structure loss			<0.1 dB/cm		
Net gain			1.7 dB/cm		
Bandwidth (12-mm section, 2.5-dB electronic gain)			115 MHz		
Combined input and output coupler loss at 4.2 K			2 dB		
Combined input and output coupler SWR at room temperature:					
frequency in GHz	13.5	14.5	15.5	16.5	17
SWR	1.6	1.25	1.15	1.25	1.8
Pump power input			50 mW		
Chromium concentration			0.05 percent by weight		

The coupling of electromagnetic energy into the high permittivity dielectric was effected by a sapphire and rutile wedge shown in Fig. 1(a). The effectiveness of the transition was investigated by measuring the standing-wave ratio (SWR) and the loss of the identical input and output transitions connected back to back; the minimum SWR of 1.15 was observed at 15.5 GHz, the value rising to 1.60 and 1.80 at 13.5 and 17 GHz, respectively, as shown in Table I. The insertion loss measured in the same frequency range was 4 ± 0.2 dB at room temperature, dropping to 2 dB at 4.2 K.

Isolation in the test section was provided by a 5-μm layer of $Ni_{0.7}Zn_{0.3}Fe_2O_4$ ferrite located in the E plane of the waveguide cross-section with approximately circular polarization of the magnetic field as shown in Fig. 1(b). The composite structure was fabricated by grinding the doped rutile slab to three quarters of the required waveguide width, depositing the ferrite on a complementary slab of undoped rutile, cementing the two sections together, and finishing the composite slab to the final shape of the waveguide cross section. The ferrite resonance at 15.7 GHz required the magnetic of 3.65 kG, the linewidth being 3.6 kG, corresponding to 8.3 GHz; the chromium spin resonance at 3.35 kG thus lies within the effective range of the isolator, the reverse and forward loss of which were 3 dB/cm and less than 0.2 dB/cm, respectively.

The performance and some parameters of the device are summarized in Table I.

The results obtained indicate that the 3-dB bandwidth of an amplifier with 30-dB electronic gain would be 115 MHz $[3/(30-3)]^{1/2} = 38$ MHz [3]. Allowing for possible degradation of the device performance, it could be expected that an operational system with a 15-cm structure would provide 30-dB electronic gain with 30-MHz bandwidth. To accommodate the 15-cm structure within the dimensions of commercially available single-crystal boules (typical dimensions—$\frac{3}{4}$ in diameter, $1\frac{1}{2}$ in long), the structure can be ground in the shape of a meandering line with fifteen 16-mm straight sections (the feasibility of the fabrication was tested by constructing a U-section of the line).

The maser constructed is interesting in that it is the first of its type to employ the double-amplification mode of operation. The experience indicates that the use of the mode should be limited to conditions precluding the use of push–pull pumping scheme. The disadvantages of the mode are the need for precise orientation of the magnetic field (misalignment by several tenths of a degree had a strong adverse effect on the performance) and the reduction of the overall filling factor due to unequal filling factors of the 1–2 and 3–4 transitions.

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References

[1] H. J. Gerritsen, S. E. Harrison, and H. R. Lewis, "Chromium-doped titania as a maser material," *J. Appl. Phys.*, vol. 31, pp. 1566–1571, Sept. 1960.

[2] H. Inaba and S. Yoshikawa, Rep. Annu. Joint Conv. IEE Japan, no. 1193, July 1960.

[3] A. E. Siegman, *An Introduction to Lasers and Masers*. New York: McGraw-Hill, 1971, p. 281.

The Electrical Characterization of a Right-Angled Bend in Microstrip Line

R. HORTON

***Abstract*—An approach to the solution of the equivalent electrical length, and the additional capacitance, associated with a right-angled bend in microstrip line are outlined. The calculations were performed under static assumptions, corresponding to a quasi-TEM mode of propagation of the fields.**

Although little theoretical work existed for comparison at the time of writing, encouraging reinforcement was gained with experimental results cited from the literature.

Introduction

Reliable design data for the fabrication of microstrip circuitry require not only information on wavelength and impedance of the infinitely long microstrip line, but also an adequate electrical description of the variety of discontinuities which commonly occur.

To this end, numerous workers in the microwave field have contributed significantly, both theoretically and experimentally, and notable attempts have been the treatment of "T"-junctions and impedance steps by Wolff, Kompa, and Mehran [1], the end effect by Farrar and Adams [2], a gap in microstrip line by Maeda [3], and the experimental contributions of Napoli and Hughes [4], Troughton [5], and Stephenson and Easter [6].

In this short paper an attempt to characterize the electrical behavior of a right-angled bend in microstrip line is made under the assumptions of static conditions. This is tantamount to the approximation of a quasi-TEM mode of propagation together with the understanding that the size of the discontinuity is small compared with the wavelength. The drawback of such an approach therefore lies in its inadequacy to completely describe the energy stored in the region of the bend, where higher order modes of an evanescent type will be excited. However, for the substrate material evaluated, it is believed that the solutions should be in good agreement with experiments up to about 10 GHz.

The calculations fall into two distinct categories. First, the current path length around the bend is evaluated, producing an equiva-

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