Our results suggest that the attenuation of the waveguide is significantly lower near cutoff than at high frequencies and that the dimensional resonance can be utilized at the same frequency to more effectively confine the wave to within the dielectric. This implies that operation of a dielectric image guide near cutoff may be advantageous for some purposes. Near cutoff the dispersion and attenuation are strong functions of the frequency; therefore our more exact approximate calculation may be critical for the design of devices in this region.

IV. Discussions and Conclusions

We introduced a new factor F_0/F_1 (which arises simply from Maxwell's equations) into the transcendental equation for the transverse propagation constant. Using this higher order approximate equation, we have calculated dispersion, dielectric losses, and conductivity losses of a dielectric image guide. Our results differ significantly from previous results [3] at low frequencies. We found that propagation losses have a minimum at low frequencies near cutoff. In addition, we found that the transverse attenuations show resonance behavior. Such resonances are dimensionally related. By measuring coupling losses near cutoff, it may be possible to characterize precisely the mode characteristics of an image guide. Our new results suggest that the operation of a dielectric image guide near cutoff may be advantageous for some applications.

Acknowledgment

The authors wish to express appreciation to J. Diaz for his discussion and aid in programming.

References

[1] E A J. Marcatili, "Dielectric rectangular waveguide and direction coupler for integrated optics," *Bell Syst Tech. J.*, vol. 48, no 7, pp. 2079–2102, Sept 1969.

[2] J E Geoll, "A circular-harmonic computer analysis of rectangular dielectric waveguides," *Bell Syst. Tech. J*, vol 48, no. 7, pp 2133–2160, Sept 1969

[3] P P Toulios and R M. Knox, "Rectangular dielectric image lines for millimeter integrated circuits," in *Proc. Wescon Conf* (Los Angeles, CA), 1970, pp 1–10

[4] R. M Knox and P. Toulios, "Integrated circuits for the millimeter through optical frequency range," in *Proc Symp. Submillimeter Waves* (NY), Apr 1–2, 1970, pp 497–516

[5] W McLevige, T. Itoh and R Mittra, "New waveguide structures for millimeter wave and optical integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol MTT-23, pp 788–794, Oct. 1975

[6] P Bhartia and I. J. Bahl, *Millimeter Wave Engineering and Applications* New York: Wiley, 1984, ch 6

[7] T Itoh, "Inverted strip dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. Microwave Theory Tech*, vol. MTT-24, pp 821–827, Nov 1976

[8] K Solbach and I. Wolff, "The electromagnetic fields and phase constants of dielectric image lines," *IEEE Trans. Microwave Theory Tech*, vol MTT-26, pp 266–274, Apr 1978.

[9] R Mittra, Y. L. Hou, and V. Jamnejad, "Analysis of open dielectric waveguides using mode matching technique and variational methods," *IEEE Trans Microwave Theory Tech*, vol. MTT-28, pp 36–43, Jan 1980

[10] U Crombach, "Analysis of single and coupled rectangular dielectric waveguides," *IEEE Trans Microwave Theory Tech.*, vol. MTT-29, pp 870–874, Sept 1981

[11] K Ogusu, "Numerical analysis of the rectangular dielectric waveguide and its modifications," *IEEE Trans Microwave Theory Tech*, vol MTT-25, pp 874–885, Nov 1977

[12] M Ikeuchi, H Sawami, and H. Niki, "Analysis of open-type dielectric waveguides by the finite element iterative method," *IEEE Trans Microwave Theory Tech.*, vol MTT-29, pp 234–239, Mar. 1981.

A 4.5-GHz GaAs Dual-Modulus Prescaler IC

MASANOBU OHHATA, MEMBER, IEEE, TOHRU TAKADA, MASAYUKI INO, MEMBER, IEEE, NAOKI KATO, MEMBER, IEEE, AND MASAO IDA

***Abstract*—A 4.5-GHz 100-mW GaAs divide-by-256/258 dual-modulus prescaler with a reset function has been developed. The operating frequency obtained for this modulus prescaler is the highest to date, while the power dissipation is comparable to others that have been reported. The supply voltage is as low as 3 V. A low-power, source coupled FET logic (LSCFL) using novel level shift circuits and 0.5-μm-gate buried P-layer SAINT (BP-SAINT) FET's have been used to achieve this high performance.**

I. Introduction

Prescaler IC's that operate in the gigahertz frequency range under low power dissipation are required for battery-operated portable radios. Many prescalar IC's using low power, source coupled FET logic (LSCFL) [1] have been fabricated to take advantage of the excellent characteristics of this logic, such as high speed and large noise margin. Several attempts to reduce the operating current at a 4 to 5 V supply voltage have been reported [2], [3].

In this letter, we report an even lower supply voltage operation. Not only by reducing the current, but also lowering the supply voltage is an effective way to extend the battery lifetime by changing the battery connection to parallel. Alternatively, by lowering the supply voltage, fewer batteries are needed. This can obviously help to reduce radio size and weight.

A 4.5-GHz 100-mW GaAs divide-by-256/258 dual-modulus prescaler with a reset function has been successfully fabricated using a three-level series gate LSCFL with novel level shift circuits [4] and new FET fabrication technology (buried P-layer SAINT) [5]. The 4.5-GHz operation is the highest modulus prescalar so far reported. The supply voltage, at 3 V, is the lowest value reported among LSCFL prescaler IC's. In addition, a reset function has been introduced to the newly designed prescaler for a phase-initialized frequency synthesizer [6] to reduce standby power dissipation.

II. Circuit Design

A block diagram of the fabricated divide-by-256/258 dual-modulus prescaler is shown in Fig. 1 The prescaler consists of three D-type master–slave flip-flops (D-FF's), six T-type master–slave flip-flops (T-FF's), two NOR gates, three OR gates, and four I/O buffers. These circuits are constructed using a three-level series gate LSCFL that offers the advantages of high speed, low power dissipation, and wide allowable threshold voltage variation, because of its true and complementary operation [1]. The NOR1 and NOR2 gates are included in DFF1 and DFF3, respectively, using a series gating technique. All FET's are normally-off types with a threshold voltage of 0.1 V. Divide-by-256 and 258 operations are selected by a mode control terminal (MC). Divide-by-256 is selected when the MC is set at a high level, and divide-258 is selected when the MC is set at a low level, or left open. The output signal is fixed at the low level when the reset terminal (R) is set at the high level. This reset function is the first attempt for the phase-initialized frequency synthesizer.

Manuscript received March 16, 1987; revised August 14, 1987.
The authors are with the NTT Electrical Communications Laboratories, Atsugi-shi, Kanagawa Prefecture, 243-01, Japan
IEEE Log Number 8717593

0018-9480/88/0100-0158$01.00 ©1988 IEEE

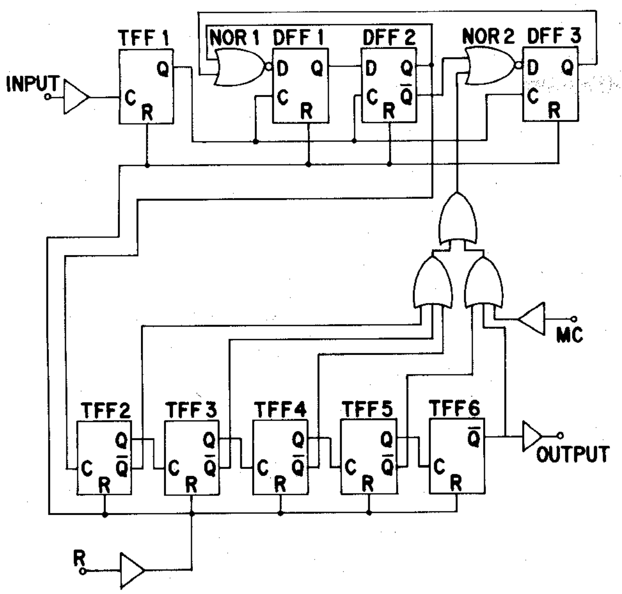

Fig. 1. Divide-by-256/258 dual-modulus prescaler.

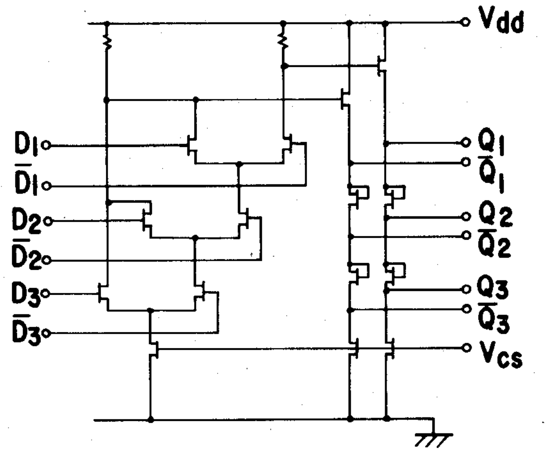

Fig. 2. Three-input OR/NOR gate using an LSCFL with new level shift circuits.

The supply voltage, which is 4 to 5 V in the conventional LSCFL, is lowered to 3 V. To achieve this reduction in voltage, a new level shift circuit [4], shown in Fig. 2, which is a three-input OR/NOR gate, was used instead of the conventional diode level shift circuit. The new level shift circuit is constructed by an FET where a gate and a drain are connected. A novel feature of this circuit is that the level shift voltage can be adjusted at the design stage by selecting an appropriate gate width and threshold voltage. By widening the gate width of the level shift FET's, the level shift voltage V_l becomes smaller. By increasing the threshold voltage, V_l becomes larger.

The gate width W_g and load resistor value R were determined by the following relation in the design:

$$W_g \times R = 22000\ (\mu\text{m ohm}).$$

The maximum and minimum gate widths are 15 μm and 5 μm, respectively. The placement of circuit blocks was optimized according to the signal flow so that signal-line length was minimized to decrease capacitance. Signal-line lengths for true and complementary signals were designed to be as close to equal as possible.

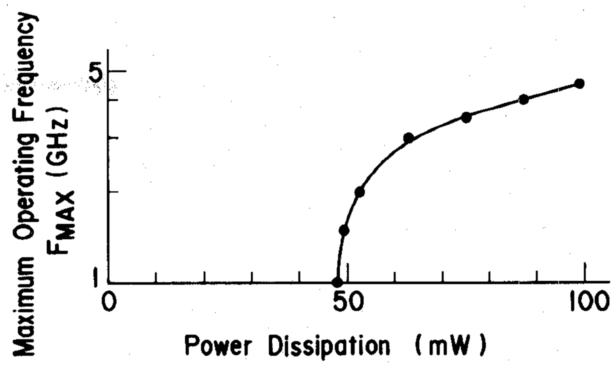

Fig. 3. Maximum operating frequency versus power dissipation.

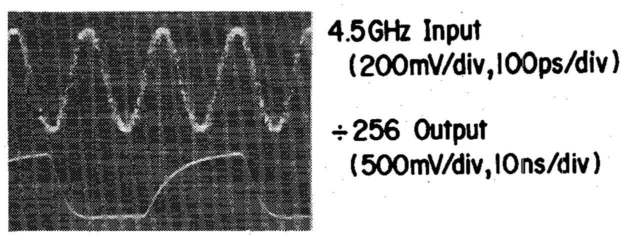

Fig. 4. Output waveforms of the divide-by-256 mode. Input frequency = 4.5 GHz.

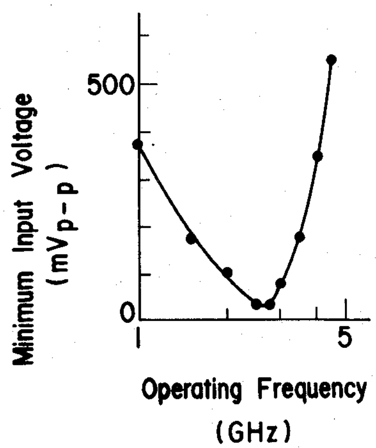

Fig. 5. Input voltage sensitivity versus operating frequency at 100 mW.

III. Performance

The prescaler IC's were fabricated using 0.5-μm-gate BP-SAINT [5] process. On-wafer probing equipment was used for prescaler performance measurements. Maximum frequency of operation F_{MAX} as a function of power dissipation is shown in Fig. 3. The F_{MAX} was 4.5 GHz with a power dissipation of 100 mW and a supply voltage of 3.0 V. This frequency is the highest reported for dual-modulus prescalers, while the power dissipation is comparable to those reported. The supply voltage can be made to be the lowest among the modulus prescalers using LSCFL owing to the new level shift circuit.

Output waveforms of the divide-by-256 and 258 modes were measured. Fig. 4 shows the output waveform of the divide-by-256 mode at an input frequency of 4.5 GHz. The output voltage amplitude is about 1 V. The output was successfully fixed at a low level when the reset terminal was set at a high level. Fig. 5 shows the input sensitivity at a power dissipation of 100 mW. The minimum input voltage is 35 $\text{mV}_{\text{p-p}}$ around a frequency of 2.5 GHz. An input voltage sensitivity of less than 0.6 $\text{V}_{\text{p-p}}$, which is small enough for portable radio applications, was confirmed for 1 to 4.5 GHz operation.

IV. Conclusions

A GaAs divide-by-256/258 dual-modulus prescaler has been developed using LSCFL with the new level shift circuits and BP-SAINT FET's. The prescaler operated up to 4.5-GHz input frequency at a supply voltage of 3 V with a power dissipation of 100 mW.

Acknowledgment

The authors wish to thank S. Saito and H. Suzuki for their valuable advice and discussion. They also wish to acknowledge T. Sugeta and M. Hirayama for their continuous encouragement and helpful suggestions.

References

[1] T Takada, Y Shimazu, K. Yamasaki, M. Togashi, K. Hoshikawa, and M. Ida, "A 2Gb/s throughput GaAs digital time switch LSI using LSCFL," *IEEE Trans Microwave Theory Tech*, vol. MTT-33, pp. 1579–1584, Dec. 1985

[2] S Saito, T Takada, and N Kato, "A 5 mA 1 GHz GaAs dual-modulus prescaler IC," *IEEE J Solid-State Circuits*, vol. SC-21, pp. 538–543, Aug. 1986

[3] K Hasegawa, T. Uenoyama, K. Nishii, and T. Onuma, "Low dissipation current GaAs prescaler IC," *Electron Lett.*, vol 22, no. 5, pp 251–252, Feb 1986

[4] M Ohhata, T Takada, M. Ino, and M Ida, "Level shift circuits for GaAs low power source coupled FET logic," *Trans. IEICE* (JAPAN), vol. E70, no 4, pp 224–226, Apr. 1987

[5] K Yamasaki, N Kato, and M Hirayama, "Below 10ps/gate operation with buried P-layer SAINT FETs," *Electron Lett*, vol 20, no. 25/26, pp 1029–1031, Dec. 1984

[6] to be submitted

GaAs on Si as a Substrate for Microwave and Millimeter-Wave Monolithic Integration

M. I. AKSUN AND H. MORKOÇ, FELLOW, IEEE

***Abstract* — Recent advances in GaAs growth on Si have resulted in high-quality and high-performance GaAs electronic and optoelectronic devices on Si substrates. One therefore must consider this composite structure as a substrate material for microwave and millimeter-wave monolithic integrated circuits. In order for GaAs on Si to be practical for this purpose, the dielectric loss must be small. We have calculated the dielectric losses of GaAs/Si composite in a transmission line configuration and compared them with those of other possible substrates, such as GaAs and Si alone, in the frequency range of 10–100 GHz. Depending upon the thickness, results show that high-resistivity GaAs epitaxial layers on Si substrates having moderate resistivities reduce the dielectric loss.**

I. Introduction

Since Hyltin examined Si as a transmission line medium for monolithic microwave integration [1], there has been a great deal of activity in the search for the most suitable substrate for monolithic microwave and millimeter wave integration [2]–[4]. So far, most of the efforts have been concentrated on Si and GaAs materials because of the availability of three-terminal devices on these substrates. Although microwave and millimeter-wave sources (IMPATT and Gunn diodes) [5] and passive components (transmission lines, Lange couplers, Wilkinson splitters, etc.) [6] have already been achieved monolithically by using either Si or GaAs substrate, both substrates have some disadvantages and advantages when compared with each other. Si is available in large area wafers and has advance processing technology. Si is also mechanically sturdy and has a larger thermal conductivity than GaAs but is not capable of producing optical sources (lasers, LED's) and low-noise millimeter-wave three-terminal devices which are already available on GaAs substrates. If high-quality GaAs layers can be grown on Si substrates, the aforementioned disadvantages of each can be remedied. Moreover, such a process opens the possibility of monolithic integration of GaAs and Si-based devices [7].

GaAs-based three-terminal devices on Si substrates, such as metal semiconductor field effect transistors (MESFET's) [8], modulation doped field effect transistors (MODFET's) [9], and heterojunction bipolar transistors (HBT's) [10], have already been demonstrated with performances nearly identical to those grown on GaAs substrates. Therefore, one of the remaining potential problems is identifying whether or not the dielectric loss of this composite material, GaAs/Si, is small enough to allow transmission line media in the microwave and the millimeter-wave region. We have thus undertaken a theoretical study of shielding microstrip lines on GaAs/Si up to 100 GHz for various parameters in Si and GaAs. The dielectric losses in GaAs, Si, and GaAs/Si materials have been investigated and compared.

II. Theory

The characteristics of a shielded microstrip line with double-layer substrate, Fig. 1, were investigated by using the spectral-domain analysis in which hybrid mode representation is used [11], [12]. Since spectral-domain analysis has been described for shielded multilayer dielectric with arbitrary coplanar conductors [13], [14], it is briefly reviewed here for double-layer substrate.

The total field in the structure can be obtained by a superposition of the TE and TM fields, which can be derived from the scalar electric and magnetic potentials ψ^e and ψ^h, respectively. Here the field components in each layer can be obtained as follows:

$$E_{zi} = j\frac{k_i^2-\beta^2}{\beta}\psi_i^e(x,y)\,e^{-j\beta z} \tag{1}$$

$$H_{zi} = j\frac{k_i^2-\beta^2}{\beta}\psi_i^h(x,y)\,e^{-j\beta z} \tag{2}$$

$$\overline{E}_{ti} = \nabla_t\psi_i^e(x,y)\,e^{-j\beta z} - \left(\frac{\omega\mu}{\beta}\right)\hat{a}_z x \nabla_t\psi_i^h(x,y)\,e^{-j\beta z} \tag{3}$$

$$\overline{H}_{ti} = \left(\frac{\omega\epsilon_i}{\beta}\right)\hat{a}_z x \nabla_t\psi_i^e(x,y)\,e^{-j\beta z} + \nabla_t\psi_i^h(x,y)\,e^{-j\beta z} \tag{4}$$

where the subscript i denotes the regions inside the shield and

Manuscript received December 4, 1986; revised August 10, 1987. This work was supported in part by the Air Force Office of Scientific Research

The authors are with the Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL 61801.

IEEE Log Number 8717592