Capacitive-Division Traveling-Wave Amplifier with 340 GHz Gain-Bandwidth Product

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Abstract

We report capacitive-division traveling-wave amplifiers having measured midband gains of 8 dB with a 1–98 GHz 3-dB-bandwidth, and 11 dB gain with a 1–96 GHz bandwidth. The capacitive-division topology raises the input Q of each cell, giving the amplifier increased bandwidth over conventional designs with the same active device technology; using 0.15–µm gate length InGaAs/InAlAs HEMTs, bandwidths exceeding 150 GHz are feasible.

Introduction

Broadband millimeter-wave amplifiers have applications as general-purpose gain blocks in satellite communication and radar systems, in very high rate fiber-optic data transmission systems, and in broadband instrumentation. Majidi-Ahy [1] reported a InGaAs/InAlAs HEMT traveling-wave amplifier (TWA) with 5.5 dB gain and a 5–105 GHz bandwidth, while Madden [2] has reported a TWA with 11 dB gain to 75 GHz. Here we report capacitive-division traveling-wave amplifiers (CDTWAs) that provide 8 to 11 dB midband gain and bandwidths as large as 98 GHz.

Capacitive division TWAs employ a capacitive voltage divider at the gates of the common-source transistors of the cascode cells, reducing the gate signal voltages (fig. 1a). Capacitive division was introduced by Ayasli [3] to increase the drive current of traveling-wave power amplifiers. Camilleri [4] reported a TWA with capacitive division (4 dB gain, 70 GHz bandwidth), but the division ratios were close to unity (0.75:1 and greater) and were varied through the amplifier to equalize the drive voltage between HEMTs, an approach varying significantly from that described here. We show here that capacitive division ratios much smaller than unity permit substantial improvements in HEMT TWA bandwidth. Capacitive-division TWA bandwidths exceeding 150 GHz are feasible using 0.15 µm InGaAs/InAlAs HEMTs.

Design

The capacitive-division TWA is shown in fig. 1a. To simplify discussion, here the normal high-impedance line sections are modeled by inductors and a highly simplified HEMT model (fig. 1b) is assumed. The HEMT parameters scale with gate width W_g (device size) as

$R_i = \tilde{R}_i / W_g$, $C_{gs} = \tilde{C}_{gs} W_g$, $g_m = \tilde{g}_m W_g$, and $R_{ds} = \tilde{R}_{ds} / W_g$. The amplifier has N cascode cells.

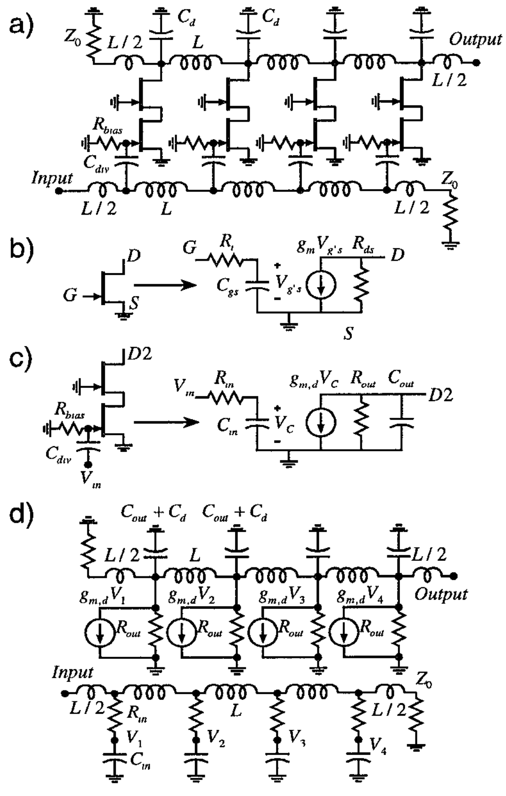

Figure 1: Capacitive-division traveling-wave amplifier (CDTWA) small-signal model (a), simplified HEMT model (b), capacitive-division cascode cell schematic and equivalent circuit (c), and CDTWA small-signal model (d) incorporating the cascode-cell equivalent circuit.

If R_{bias} is large the HEMT cascode pair with input division capacitor C_{div} is approximated by the network of fig. 1c, with an input capacitance $C_{in} = MC_{gs}$, a degenerated transconductance $g_{m,d} = Mg_m$, an output resistance $R_{out} \cong R_{ds}(1 + g_m R_{ds})$, and an output capacitance $C_{out} \cong C_{gs} / (1 + g_m R_{ds})$. $M \cong C_{div} / (C_{div} + C_{gs})$ is the voltage division ratio between C_{div} and C_{gs}. The resulting amplifier model is shown in fig. 1d. The capacitive-division circuit reduces to the simple TWA if $M = 1$ (e.g. $C_{div} >> C_{gs}$).

The gate synthetic transmission line has characteristic impedance $Z_g = L^{1/2} C_{in}^{-1/2}$, and per-section attenuation $\exp(-\alpha_g)$, with $\alpha_g \cong (2\pi f)^2 C_{in}^2 R_i Z_g / 2$. Similarly, the drain transmission line has characteristic impedance $Z_d = L^{1/2} (C_{out} + C_d)^{-1/2}$ and per-section attenuation $\exp(-\alpha_d)$, with $\alpha_d \cong Z_d / 2R_{out}$. By design, $Z_g = Z_d = Z_0 = 50\Omega$. The gate and drain synthetic line cutoff frequencies $f_{Bragg,g} = \pi^{-1} L^{-1/2} C_{in}^{-1/2}$ and $f_{Bragg,d} = \pi^{-1} L^{-1/2} (C_{out} + C_d)^{-1/2}$ can be set arbitrarily high by using a large number N of small transistors (small W_g), and do not normally limit the attainable bandwidth.

Attainable bandwidth is set by gate line attenuation. The input voltage to the N^{th} HEMT is reduced by $\sim \exp(-N\alpha_g)$, and transistors far from the input are not driven strongly at high frequencies [5]. The amplifier bandwidth f_{high} is thus found by setting $N\alpha_g = N(2\pi f_{high})^2 C_{in}^2 R_i Z_g / 2 \approx 1/2$, while the midband gain is $|S_{21}| = NM g_m Z_0 / 2$ and $C_{in} = MC_{gs}$. Combining these,

$$|S_{21}| f_{high}^2 \approx \frac{1}{2M} \cdot \frac{g_m}{4\pi^2 R_i C_{gs}^2} = \frac{1}{2M} \cdot \frac{f_\tau}{2\pi R_i C_{gs}} \quad (1)$$

Eq. (1) gives the feasible bandwidth versus gain. For a simple TWA, $M = 1$ and $|S_{21}| f_{high}^2 \approx f_\tau / 4\pi R_i C_{gs}$; for a given gain, capacitive division increases the feasible bandwidth by $M^{-1/2}$. The improved bandwidth predicted by the simplified analysis above is confirmed through simulations using full circuit models for both the (lossy) inductive line sections and the 0.15–µm

InGaAs/InAlAs HEMTs (fig. 2). Bandwidth cannot be increased without bound, as drain line attenuation becomes significant for small M. Gain versus bandwidth ultimately reaches limits set by the cascode cell's maximum available gain (fig. 2). Additionally, the HEMT gatewidths become large, making circuit layout problematic.

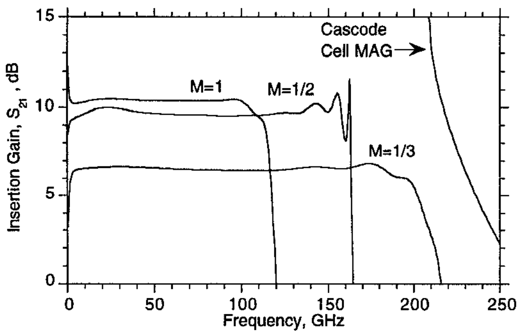

Figure 2: Simulated gain-frequency characteristics for a simple TWA ($M=1$) and CDTWAs ($M=$ 1/2 and 1/3), compared to the cascode cell's maximum available gain.

Implementation & Results

Using 0.15–μm gate length, InGaAs/InAlAs HEMTs with f_{max}=270 GHz and $f_\tau \cong$160 GHz [6], we have fabricated CDTWAs with $M=$ 1/2, $N=$ 7 and with a 105 GHz design bandwidth.

Circuits from 2 wafers were tested with a 7-200 GHz active wafer probe system [7]. 8 dB midband gain with a 98 GHz 3-dB-bandwidth (fig. 3a) and 10 dB midband gain with a 92 GHz 3-dB-bandwidth (fig. 3b) are obtained. Bandwidth is presently limited by $f_{Bragg,d}$, which is 10% lower than designed. The strong positive gain slope indicates that higher gain-bandwidth products are feasible. With reduced drain-source bias on the common-source transistors, flat gain (10.6±0.65 dB from 2.8–50 GHz) is obtained, as measured by a commercial 50 GHz network analyzer (fig. 3c), while 11 dB gain and a 96 GHz 3-dB-bandwidth are measured using a W-band network analyzer (fig. 3d). The latter measurement corresponds to a 340 GHz voltage-gain × bandwidth product. Differences between the 4 measurements reflect both bias conditions and variations in the HEMT gate length and gate recess depth, as each measurement was taken from circuits on a different wafer.

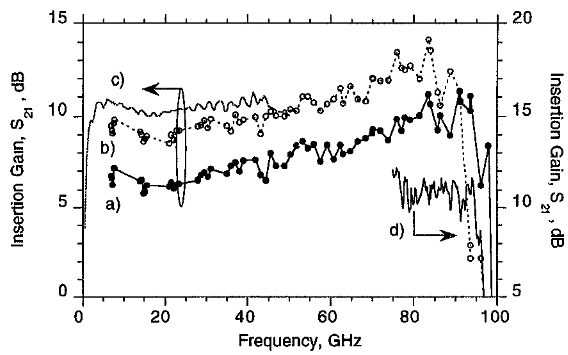

Figure 3: Gain-frequency characteristics for CDTWAs on wafer S005-40 (a), S005-39 (b) measured by an active probe system, wafer V1239 (c), measured on a DC-50 GHz microwave network analyzer, and wafer V1238 (d), measured on a W-band microwave network analyzer.

In summary, capacitive division TWAs have been designed and fabricated which achieve 340 GHz gain-bandwidth product. Capacitive division significantly increases attainable bandwidths. Designs using InGaAs/InAlAs HEMTs and $M=$ 1/3 (M is lowered to take further advantage of capacitive division) are in process and should obtain bandwidths in excess of 150 GHz. Fiber-optic transmission systems operating at rates above 100 GB/sec are a key application.

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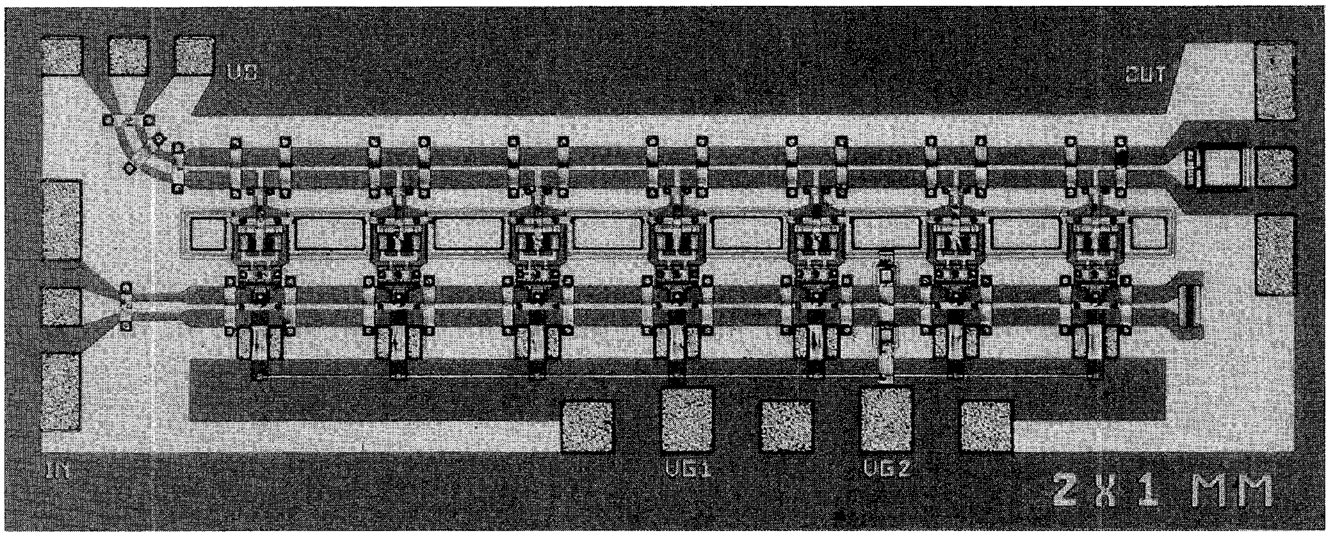

Figure 4: Photomicrograph of the 0.7 mm by 2 mm die.

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