Generation of 3.5-ps Fall-Time Shock Waves on a Monolithic GaAs Nonlinear Transmission Line

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Abstract—Picosecond electrical transients were generated by shock-wave formation on a monolithic GaAs nonlinear transmission line (NLTL). An output fall time of 4.3 ps was measured for a single line driven at 15 GHz (20-ps fall time) while a cascade of two lines driven at 8 GHz (37-ps fall time) produced a 2-V waveform with 3.5-ps fall time.

I. INTRODUCTION

CIRCUITS for generation of picosecond transition-time electrical signals are central to wide-bandwidth time-domain and microwave sampling instrumentation. Specifically, the bandwidth of diode sampling bridges used in sampling oscilloscopes, network analyzers, and microwave frequency counters is limited by the transition time of the signal gating the diodes. This fast electrical transition can be generated by shock-wave formation on a nonlinear transmission line (NLTL) [1]-[3]. Previously, we had proposed a monolithic GaAs NLTL [4] and demonstrated compression of 10-ps fall-time sine wave to 7.8-ps output on devices with 3-µm features on which an 8-GHz sinusoidal input had been used to generate a 2-V sawtooth output with 3.5-ps fall time. This transition time is an order of magnitude shorter than that reported for step recovery diode (SRD) signals used for diode signal gating the diodes. This fast electrical transition can be fabricated on GaAs wafers [5]. Here we report devices with 10-µm minimum feature size [5]. Here we report devices with a 20-ps fall time while a cascade of two lines driven at 8 GHz propagates a 2-V wavefront with 3.5-ps fall time.

A circuit diagram for the NLTL is shown in Fig. 1(a). A high-impedance transmission line with characteristic impedance $Z_1$ is periodically loaded, at spacing $\tau$ (in units of time), by Schottky varactor diodes, producing a synthetic transmission line whose propagation velocity is voltage-dependent. As a negative-going input voltage transition with initial voltage $V_0$, final voltage $V_f$, and fall time $t_f$, propagates along the line, the fall time will at first decrease linearly with distance due to the differential group delay, $\Delta t = T(v_o) - T(v_f)$, along the waveform where $T(v) = n\sqrt{LC_T'(v)}$ [2]. $L = Z_1\tau$ is the inductance per line section, $n$ is the number of diodes in the line, $C_T(v) = C_f(v) + \tau/Z_1$ is the total capacitance per section, and the capacitance of a step-junction diode with junction potential $\phi$ is $C_f(v) = C_{j0}/\sqrt{1-v/\phi}$. As the fall time decreases, dispersion arising from the periodic-line cutoff frequency, $\omega_c = 2\sqrt{LC_{j0}}$, and the varactor cutoff frequency, $\omega_c = 1/r_Cj_0$, competes with the compression arising from the voltage-dependent propagation velocity. Here $C_{j0} = (Q_{j0} - Q_{j0}(V_f))/V_f$ is the varactor large-signal capacitance and $r_C$ is the diode series resistance. A final limited fall time $T_{f,\text{lim}}$ is reached at which the fall-time compression per line section is equal to the fall-time broadening per section so that the resulting shock wave propagates unchanged. The fall time at the output of the line will be [1]

$$T_{f,\text{out}} = \max \left\{ \frac{T_{f,\text{lim}} - \Delta t}{T_{f,\text{lim}}}, \frac{3}{2}\frac{8.8}{\omega_c} \frac{1}{\sqrt{1 - V_f/\phi}} - 1 \right\}$$

If $\omega_c \ll 5\omega_{ph}$ and $V_f = 0$, then

$$T_{f,\text{lim}} = \frac{8.8}{\omega_c} \frac{1}{\sqrt{1 - V_f/\phi}} - 1$$

while simulations indicate that if $\omega_c \gg 5\omega_{ph}$ then $T_{f,\text{lim}} \approx 3/\omega_{ph}$. With monolithic fabrication on GaAs, $\omega_c$ and $\omega_{ph}$ on the order of 0.2-2 THz are feasible [6], permitting compressed fall times on the order of 0.5-5 ps.

Three NLTL designs were fabricated. A full-scale design had diodes with $C_{j0} = 50$ fF and $\omega_c/2\pi = 800$ GHz which were spaced 160 µm apart ($\tau = 1.6$ ps) resulting in $\omega_{ph}/2\pi = 110$ GHz. In a half-scale design (Fig. 1(b)), the diode spacing was reduced to 80 µm, increasing $\omega_{ph}$. Since the large-signal wave impedance $Z_{j0} = \sqrt{L/(C_{j0} + \tau/Z_1)}$ was constrained to be 50 Ω, $C_{j0}$ must scale with $\tau$, so $C_{j0}$ was scaled to 25 fF. Nonlinear circuit simulations using SPICE indicate (Fig. 2) that for the full-scale NLTL a 20-ps input is compressed to a limiting fall time of 4.7 ps after 60 diodes while on the half-scale line an 8-ps transition will have a 2.7-ps fall time after 45 diodes. To reduce layout parasitics on the half-scale line, the coplanar waveguide dimensions are also scaled, resulting in...
increased loss. To minimize loss, a mixed design used a full-scale line to compress to 6-ps fall time and a half-scale structure to compress to ~3.0 ps. A cascade of two different 1-cm-long NLTL designs would then be needed to compress a 40-ps fall-time input signal, a 64 diode full-scale line and a mixed structure with 48 large diodes, a constant impedance taper, and 32 small diodes.

III. FABRICATION

A cross section through a diode is shown in Fig. 3. Schottky diodes are formed on GaAs MBE material with a 0.6-μm N− active layer (3 × 10¹⁶/cm² doping). A buried 0.8-μm N+ layer (6 × 10¹⁸/cm² doping) provides both the diode cathode connection and a resistive connection between the two coplanar waveguide ground planes, suppressing propagation of the slot-line mode. Ohmic contacts having 0.02-Ω-mm resistivity are formed by a 0.75-μm recess etch, a self-aligned (88-percent Au-12-percent Ge)/Ni/Au lift-off, and a 450°C alloy. Proton implantation [7] using both 190 keV, 1 × 10¹⁵/cm² and 110 keV, 2 × 10¹⁵/cm² provides >40-MΩ/sq isolation. During implantation, a 1.7-μm Au mask on top of a 1.4-μm polyimide layer [8] protects the ohmic contacts and the diode active region. The interconnections are formed with a 0.1-μm Ti/0.1-μm Pt/1.4-μm Au lift-off. Schottky diodes are formed in regions where the 5-μm-wide center conductor overlaps unimplanted N+ material.

IV. RESULTS AND DISCUSSION

Circuit element values for the completed structures were established through I-V, C-V, and small-signal scattering parameter measurements. Both NLTL circuits had Z1 = 90 Ω while Z0(v) varied from ~44 to 54 Ω and ΔT ≈ 35 ps as the dc bias varied from 0 to ~6 V. The center conductor dc resistance, rj = 22 Ω, on the large-scale line contributed to a 4.5-dB loss at 15 GHz. The mixed structure had rj = 25 Ω and 5.0-dB loss.

The circuit performance was evaluated by direct electrooptic (EO) sampling [9], [10] of the voltage waveforms launched onto the line through microwave wafer probes. The EO sampling system uses a pulse-compressed, CW mode-locked Nd:YAG laser to noninvasively probe internal nodes of IC's. Auto correlation measurements of the laser pulses indicated that their 1.25-ps FWHM duration resulted in a system bandwidth approaching 200 GHz while software deconvolution put a lower bound of 1.8 ps on the system rise time when configured as a sampling oscilloscope. We tested the fall-time compression of the NLTL with both sinusoidal (where the 10-90-percent rise time is 0.3 cycles) and SRD step output signal excitation. The formation of shock waves on the NLTL is similar in each case, although higher loss occurs with sinusoidal drive [1], and the calculated minimum compressed fall time is the same [11].

Under 23-dBm sinusoidal drive at 15 GHz (20-ps fall time) a large-scale line generated a 6.5-ps transition while a mixed line produced a 4.3-ps fall time. Fig. 4 shows both the output and input signals for a cascade of a full line and a mixed line structure driven at 8 GHz and 23-dBm power. A 2-V, 3.5-ps fall-time shock wave was generated. The two lines were cascaded with a pair of microwave probes connected by coaxial cable. The input waveform is the voltage at the first bondpad and clearly shows how the NLTL had been biased slightly (2.7-mA average current) into diode forward conduction. The formation of shock waves on the NLTL is similar in each case, although higher loss occurs with sinusoidal drive [1], and the calculated minimum compressed fall time is the same [11].

We have demonstrated that nonlinear wave propagation on a monolithic GaAs NLTL can form shock waves with fall time as short as 3.5 ps (undeconvolved from a measurement rise time of at least 1.8 ps). Further improvements in the device...
and circuit designs should result in generation of step functions with fall times approaching 1 ps. The present circuit could be integrated with a diode sampling bridge to give a fully monolithic sampling head with a bandwidth of approximately 100 GHz.

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REFERENCES