V-Band and W-Band Broad-Band, Monolithic Distributed Frequency Multipliers

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***Abstract*—Broad-band V-Band and W-Band frequency multiplication is reported using soliton propagation on a GaAs monolithic device. With 24-dBm input, a doubler attained 17.4-dBm peak output power with at least 52–63.1-GHz, 3-dB bandwidth, and a tripler attained 12.8-dBm peak output power with at least 81–108.8-GHz, 3-dB bandwidth. These multipliers, fabricated with 3-μm design rules on GaAs and driven by lower frequency amplifiers, have applications as cost-effective sources in mm-wave systems.**

I. Introduction

Diode-frequency multipliers driven by synthesizers are widely used as low phase noise millimeter-wave sources for receivers and instrumentation. Common multipliers are limited in either conversion efficiency or bandwidth. Implementations using diodes as nonlinear conductances cannot attain high-conversion efficiencies, while implementations using lumped-element varactors have reactive impedances which cannot be matched efficiently over a broad-bandwidth. Harmonic generation [1]–[5] can also be performed on nonlinear transmission lines (NLTL's) [6], structures having periodically distributed nonlinear capacitance. Through soliton propagation on NLTL's, harmonic generation with broad-bandwidth and high efficiency is possible.

In this work, we have improved our previous results [5] by reducing skin losses and by introducing devices for V-band and W-band output. With 24-dBm input power, we report harmonic generation in the 60-GHz band with 17.4-dBm output power, and harmonic generation in the 90-GHz band with 12.8-dBm output power. These devices do not compete directly with current HEMT power performance [7], [8], but since they are driven with lower frequency amplifiers and are processed with 3-μm design rules on GaAs, they are cost-effective sources of high-frequency power.

II. Solitons on NLTL's

Solitons are pulse-like waveforms that propagate without distortion in media having nonlinearity and dispersion. An NLTL, a ladder network of high-impedance transmission line sections periodically loaded with reverse-biased diodes (Fig. 1), exhibits nonlinearity from the diodes' voltage-variable capacitance and dispersion from the periodic network. NLTL's, therefore, support soliton propagation. If the diodes have capacitance $C_d(V)$, the line sections have impedance Z_L and delay τ, and if $C_d(V) > \tau/Z_L$, then the structure can be modeled as an LC ladder network having $L = Z_L\tau$ and $C(V) = C_d(V) + \tau/Z_L$ where for our process $C_d(V) \cong C_{jo}/(1 - V/\phi)^M$, $\phi = 1$ volt, and $M = 0.708$. At bias V_{bias}, the periodicity prevents propagation above the Bragg frequency, $f_b = 1/(\pi\sqrt{LC(V_{\text{bias}})})$. If the total capacitance $C(V)$ is approximated as $C_0/(1 - V/V_0)$, then solitons propagating on the NLTL have propagation delay per NLTL section [9], [10] of

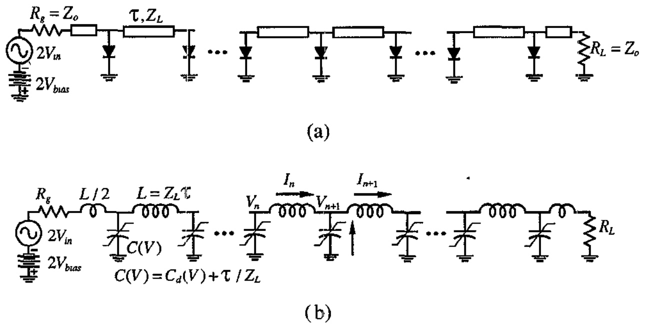

Fig. 1. (a) Nonlinear transmission line circuit diagram, and its (b) L-C ladder network equivalent circuit.

$$T_d = \sqrt{LC_0V_0/V_{\max}}\,\sinh^{-1}\left[\sqrt{\frac{V_{\max}}{V_0}}\right],$$

and FWHM pulse width

$$T_{\text{FWHM}} = 1.763\sqrt{LC_0V_0/V_{\max}}.$$

Impulses of amplitude $V_{\max}$ having duration $T_{\text{FWHM}} > 1.763\sqrt{LC_0V_0/V_{\max}}$ correspond to a nonlinear superposition of a set of solitons having differing amplitudes (i.e., different $V_{\max}$'s) and hence, differing per-section propagation delays T_d; if such an impulse is applied to the network, the impulse will decompose into a set of solitons during propagation. If instead of driving the NLTL with a single pulse, we drive it with a train of pulses (e.g., a sine wave) then each pulse separates into a set of solitons, generating a waveform with multiple pulses per cycle and hence significant harmonic content. Harmonic generation is most efficient when the Bragg frequency eliminates spectral power above the desired harmonic.

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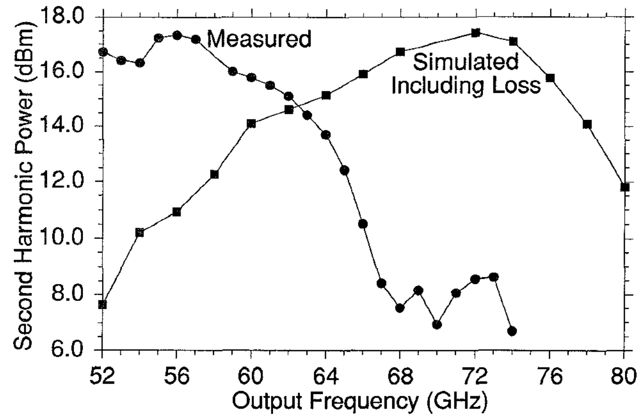

Fig. 2. Measured and simulated curves of output power versus output frequency for the frequency doubler with $f_b = 69$-GHz and 24-dBm input power.

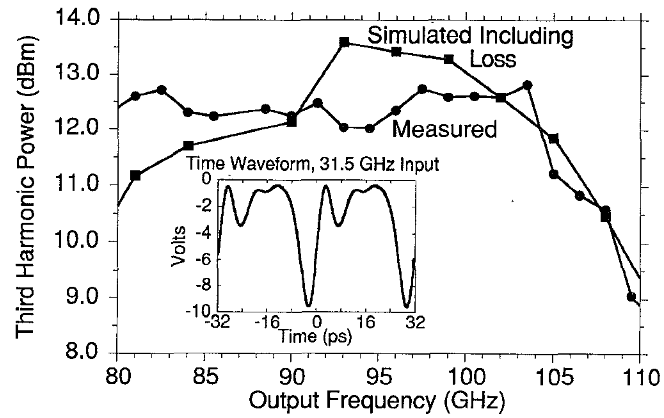

Fig. 3. Measured and simulated curves of output power versus output frequency for the frequency tripler with $f_b = 99$-GHz and 24-dBm input power.

III. Results

We have fabricated a doubler ($f_b = 69$ GHz) and a tripler ($f_b = 99$ GHz), both having a 26–40 GHz input band. Multiplier input powers were calibrated using a precision power meter, and cable and probe losses were determined with a network analyzer. Multiplier output waveforms were measured using integrated on-wafer 275-GHz bandwidth sampling circuits [11]. Samplers are calibrated by applying known input voltages, and their bandwidth determined by pulse response measurements [11]. Power spectra were obtained by numerical Fourier transformations. The diode epitaxial design and the fabrication process are described in [5]. Airbridges eliminate unbalanced modes in the coplanar-waveguide. Unlike our previous devices [5] where $Z_L = 90\ \Omega$, the current devices use $Z_L = 75\ \Omega$. These have wider signal conductors and hence, substantially lower skin losses. For the doubler, $\tau = 3.1$ ps, $C_{j0} = 105$ fF, $C_0 = 139$ fF, and $V_0 = 5.0$ V. The tripler had $\tau = 2.1$ ps, $C_{j0} = 73.0$ fF, and $C_0 = 96.7$ fF.

In Figs. 2 and 3, experimental results are compared with simulations [12], measured with 24 dBm input power (10.0 Vp-p). The V-Band doubler, biased at -4.6 volts, gives 17.4-dBm peak output power at 56 GHz and at least a 52–63.1-GHz, 3-dB bandwidth (Fig. 2). We were unable to make measurements below 52 GHz because of limitations in the source frequency range. The W-Band tripler, biased at -3.0 volts, attains better than 12 dBm output power from 81–103.5 GHz (Fig. 3). The 3-dB bandwidth of the device is at least 81–108.8 GHz with source limitations below 81 GHz output frequency. For both high-frequency devices, measurements agree with simulations to within approximately 2 dB, although the doubler simulation is shifted in frequency from the measured curve. Simulations indicate that the ≈11-V diode reverse breakdown causes significant loss and limits output power. Simulations also show that elimination of diode and skin losses increases doubler output by 1.6 dB. Given zero dissipation, efficiency is limited by leakage of 16% (P^1_{out}/P^1_{in}) unconverted fundamental and generation of 2% ($P^{3,4,\cdots}_{out}/P^1_{in}$) spurious harmonics.

IV. Summary

We have demonstrated broad-band V-Band and W-Band distributed frequency multiplication. If the breakdown voltage is increased the expected conversion loss improves to 4 dB for the V-Band doubler and 10 dB for the W-Band tripler. These monolithic frequency multipliers can be used as broad-band signal sources for mm-wave systems and instrumentation.

Acknowledgment

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