Microwave-Optoelectronic Performance of a Ridged Heterostructure Microstrip Ring Resonator

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Abstract— **Microwave-optical mixing is accomplished in a ridged heterostructure microstrip ring resonator. When compared to an identical circuit fabricated on semi-insulating GaAs, a 15-dB improvement in conversion loss is achieved.**

THE availability of broad-band optical sources and the immunity of lightwaves to electromagnetic intereference coupled with the low transmission losses of optical fibers have led to an increased interest in employing photonics for generating [1], controlling [2], receiving, and processing microwave signals. However, the drawback of employing optical techniques for microwave signal processing is the large power loss associated with optical to electrical conversion or vice versa. This problem is of particular consequence for mixers that serve as receiver front-ends. In earlier work [3], [4], we demonstrated a microwave-optical mixer on semi-insulating (SI) GaAs by monolithically integrating a photodetector into a microstrip ring resonator. We observed that the efficiency of the mixer was enhanced if the frequencies of modulated optical RF signal and the local oscillator (LO) pump signal were near one of the resonant frequencies of the microstrip ring. In this letter, we report further improvements in mixer performance (particularly the conversion loss) by employing a ridged heterostructure microstrip ring resonator.

The layout of the microstrip ring resonator circuit for microwave-optical mixing is shown in Fig. 1. Here, the microstrip lines were 274 μm wide and the mean radius of the ring was 4.73 mm. The bias pad of the circuit also serves as a low pass filter with a cutoff frequency of 2 GHz, which is below the ring's first resonance and therefore does not perturb the fields in the ring. Since the design and performance of a similar circuit fabricated on SI GaAs were discussed in good detail in [4], only aspects pertaining to the heterostructure and its influence on circuit performance will be discussed here. The hetero-epitaxial material employed in this work consists of a 2-μm active layer of undoped GaAs sandwiched between two 500-Å $Al_{0.3}Ga_{0.7}As$ layers grown on a SI GaAs substrate. This particular configuration of epi-layers offers many advantages. Since 0.84 μm was the optical wavelength of choice, photon absorption takes place mainly in the 2-μm GaAs active region with carrier confinement being provided by the two larger band-gap $Al_{0.3}Ga_{0.7}As$ layers. This limits carrier diffusion and isolates the active region from traps in SI GaAs. The top $Al_{0.3}Ga_{0.7}As$ layer serves as a window for the incident optical radiation by allowing carriers to reach the active region, while at the same time minimizing surface recombination. Thus both the RF response and dc responsivity of the photodetector were improved by employing this heterostructure.

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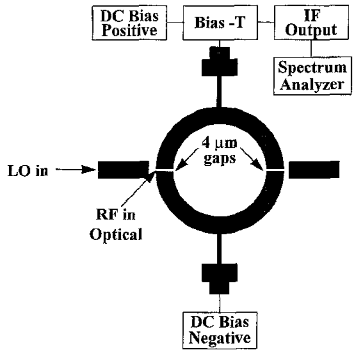

Fig. 1. Layout of circuit for microwave-optical mixing.

To pattern the circuit, conventional photolithographic techniques were employed. With reference to Fig. 1, a heterostructure ridge was first created in the regions underlying the microstrip lines of the circuit and across the 4-μm gaps in the resonator. Elsewhere in the circuit (including the gaps across feed lines), the heterostructure layers were etched down to expose the SI GaAs substrate. Gold electrodes defining the circuit were then electroplated to a thickness of about 3.2 μm following which the circuit was annealed in a resistive strip heater at 170° C to form Schottky contacts. The device was then mounted in a microwave test fixture. When a dc voltage is applied to the bias pads, the 4-μm gaps behave like a pair of Schottky diodes connected back-to-back. Since the layers are undoped, the depletion region of one of the Schottky diodes extends to the second Schottky, which makes photodetection and hence microwave-optical mixing possible.

The circuit was electrically tested in a HP-8510B network analyzer and the first three resonances were observed at 3.76, 7.42, and 10.8 GHz with loaded Q-factors of 29, 24, and 27 respectively. For an identical circuit fabricated on SI GaAs [4], resonances were observed at 3.467, 7.18, and 10.4 GHz with loaded Q-factors of 45, 58, and 78. We attribute the lower Q-

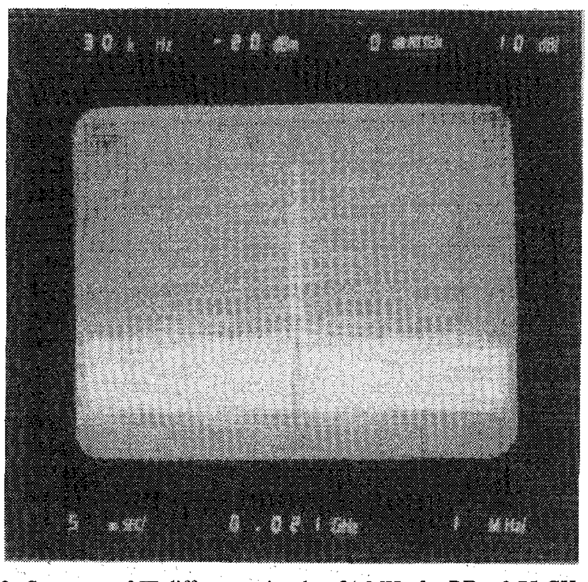

Fig. 2. Spectrum of IF difference signal at 21 MHz for RF = 3.75 GHz and LO = 3.771 GHz.

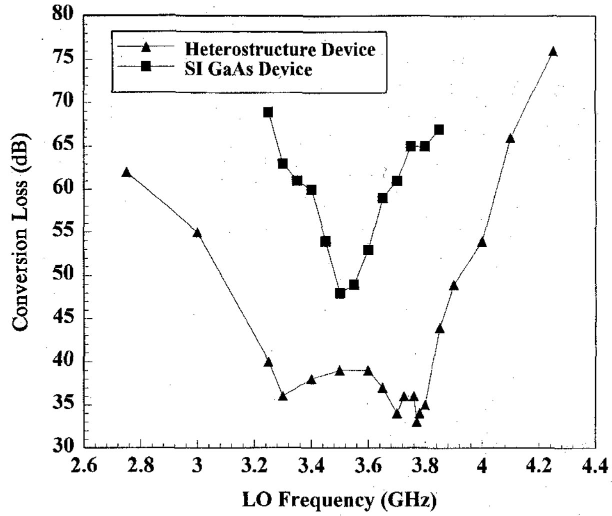

Fig. 3. Conversion loss vs. LO pump frequency of SI GaAs and heterostructure devices.

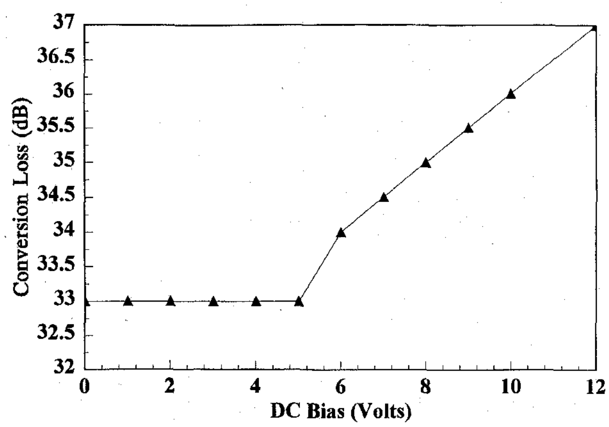

Fig. 4. Conversion loss vs. dc bias of the heterostructure device. LO pump power = +15 dBm, RF modulating power into laser = -15 dBm.

factors of the heterostructure device to conductor losses in the heterostructure layers due to unintentional doping. However, as expected, the lower Q-factors resulted in a larger mixing bandwidth. For the microwave-optical mixing experiments reported in this paper, the circuit was operated in the ''resistive mixing mode" [4]; i.e., mixing occurs due to the time-varying nature of the conductance of the 4-μm gap region of the resonator which was modulated by both the microwave LO and optical RF signals. As illustrated in Fig. 1, a LO pump signal was applied to the feed line of the resonator, and an optical RF signal at an operating wavelength of 0.84 μm (derived from a modulated laser diode) was focused onto one of the 4-μm gaps. The resulting intermediate frequency (IF) difference signal (|LO - RF|) was then extracted from the bias pad of the resonator via the bias-T. With RF and LO sources set at 3.75 and 3.771 GHz respectively, a typical spectrum of the IF difference signal at 21 MHz is shown in Fig. 2. The conversion loss of the mixer as a function of LO pump frequency for both the heterostructure and SI GaAs [4] devices is illustrated in Fig. 3. We define conversion loss (in dB) as the difference between RF input power applied to the laser diode and the detected IF signal strength at the spectrum analyzer. Hence, efficiencies of both the laser diode and the mixer are reflected in the conversion loss data. For data corresponding to Fig. 3, the laser diode was modulated with -15 dBm of input power at a frequency near the ring's first resonance (at 3.75 GHz for the heterostructure device and at 3.47 GHz for the SI GaAs device), with the LO pump power held constant at +15 dBm; in both cases, the 4-μm gaps of the resonators were dc-biased, and the bias level was optimized for maximum IF response. As shown, if the LO pump frequency is close to the first resonance of the ring the conversion loss is at its minimum, and as it is tuned away from resonance the conversion loss increases. This occurs because off-resonance frequencies are not supported by the ring. Comparing conversion losses near first resonance of the SI GaAs and heterostructure devices, a 15-dB improvement in performance is obtained in the case of the heterostructure device. Also, as shown, by virtue of its smaller loaded Q-factor, the mixing bandwidth of the heterostructure device is larger than that of the SI GaAs device. Illustrated in Fig. 4 is the conversion loss of the heterostructure device as a function dc bias across the 4-μm gaps of the resonator. Here, the LO pump power was held constant at +15 dBm. As shown, the conversion loss of the mixer increases with dc bias. This occurs at dc bias levels where the dark current due to application of bias approaches the photo-injected current. When this happens, modulation of conductivity of the 4-μm gap region, due to the photoinjected carriers, is overwhelmed by the large dark current, resulting in a larger conversion loss.

In conclusion, a ridged heterostructure microstrip ring resonator has been employed to down-convert an optically modulated RF signal to a lower IF by mixing with an electrically pumped LO applied to the resonator. When compared to an identical device fabricated on SI GaAs, a 15-dB improvement in conversion loss is obtained. This circuit could be used as a front end in optoelectronic receivers.

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REFERENCES

[1] C. H. Lee, "Picosecond optics and microwave technology," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-38, pp. 596-607, May 1990.

[2] A. J. Seeds and A. A. A. de Salles, "Optical control of microwave semiconductor devices," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-38, pp. 577-585, May 1990.

[3] G. K. Gopalakrishnan, B. W. Fairchild, C. L. Yeh, C. S. Park, K. Chang, M. H. Weichold, and H. F. Taylor, "Microwave Performance of a Nonlinear Optoelectronic Microstrip Ring Resonator," *Electronics Letters*, vol. 27, pp. 121-123, Jan. 1991.

[4] G. K. Gopalakrishnan, B. W. Fairchild, C. L. Yeh, C. S. Park, K. Chang, M. H. Weichold, and H. F. Taylor, "Experimental Investigation of Microwave-Optoelectronic Interactions in a Microstrip Ring Resonator," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-39, pp. 2052-2060, Dec. 1991.