# Degenerate Parametric Amplification in an Optoelectronic GaAs CPW-to-Slotline Ring Resonator

Jong-Chul Lee, *Member, IEEE*, Henry F. Taylor, *Fellow, IEEE*, and Kai Chang, *Fellow, IEEE*

***Abstract*—Nonlinear optical-microwave mixing is performed in an uniplanar CPW-to-Slotline ring resonator on semi-insulating GaAs substrate, in which a Schottky photodetector is monolithically integrated as a coupling gap. Parametric amplification effect of the mixer occurs when the capacitive reactance of the detector is modulated. In this structure, the parametric amplification gain of 20 dB without the applied bias in the radio frequency (RF) signal is obtained. This microwave optoelectronic mixer can be used in fiber-optic communication links.**

***Index Terms*—GaAs, optoelectronics, parametric amplification, ring resonator.**

## I. Introduction

RECENTLY, optical control in optoelectronic devices has attracted much attention because of its potential applications in signal switching, mixing, and frequency modulation. Also, nonlinear interaction between optical and microwave signals in semiconductor devices has generated much interest [1]–[4]. As a microwave-optoelectronic mixer, several attempts involving microstrip ring structures have been made on semi-insulating GaAs substrate using optical excitation [5], [6]. In an earlier work, we demonstrated the optical-microwave mixing performance of a CPW-to-Slotline ring resonator on a GaAs substrate [7].

In this letter, we report the experimental results on nonlinear performance of an optoelectronic microwave CPW-to-Slotline ring resonator in which a Schottky photodetector is monolithically integrated at a coupling gap between the CPW feed lines and the slotline ring resonator.

## II. Device Structure

The structure of the CPW-to-Slotline ring resonator is shown in Fig. 1. Here, the CPW feed lines have a 703-$\mu$m-wide conductor strip and a 305-$\mu$m-wide gap between signal and ground. The Slotline ring has inner and outer radii of 5.555 and 5.615 mm, respectively. The coupling gap is designed to be 5 $\mu$m for optical excitation. The rectangular island in the bottom of the figure is the bias pad for the device which connects through gold wire bonding to the center of the ring. The $S_{21}$ microwave characteristic of the device was measured using a HP 8510B network analyzer, and its first three resonance peaks were observed to be 4.19, 7.95, and 11.4 GHz, respectively. Also, the corresponding insertion losses were to be −11, −5.1, and −4.5 dB and the loaded $Q$ values were to be 10.5, 13.6, and 11, respectively.

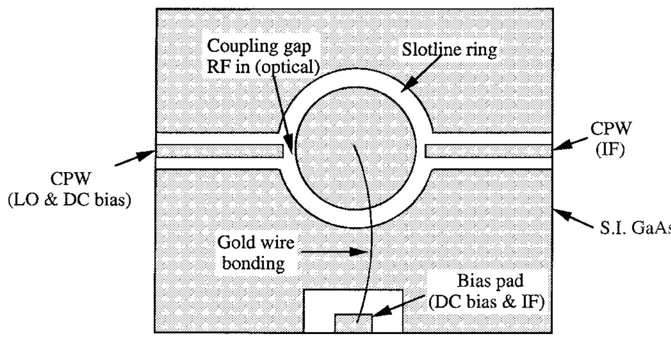


Fig. 1. The structure of the CPW-to-Slotline ring resonator.

Since the design, the fabrication process, and the intermixing effects of optical RF signals with local oscillator (LO) microwave signals including conversion loss of the device were discussed in good detail in [7], only aspects pertaining to the experiments on nonlinear parametric amplification in the CPW-to-Slotline ring resonator will be discussed in this letter.

## III. Experiments and Discussion

The parametric amplifier uses the time-varying reactive parameter to obtain amplification [8]. In the case of the CPW-to-Slotline ring resonator, the capacitance of the gap region between the feedlines and the ring acts as the time-varying reactance. In the parametric amplifier, three frequencies are generally present: the signal frequency $\omega_s$; pump frequency $\omega_p$; and an idler frequency $\omega_i = \omega_p \pm \omega_s$. Fig. 2 shows a schematic configuration of a parametric amplifier in ring resonator structure. In this experiment with the CPW-to-Slotline ring resonator, the signal source is the radio frequency (RF) modulated by optical excitation, the pumping oscillator is the LO provided by an external microwave synthesizer, and the idler circuit output is the IF extracted from the feedline or bias pad depending on operating frequency range. $C(t)$, the time-varying capacitance which comes from a Schottky

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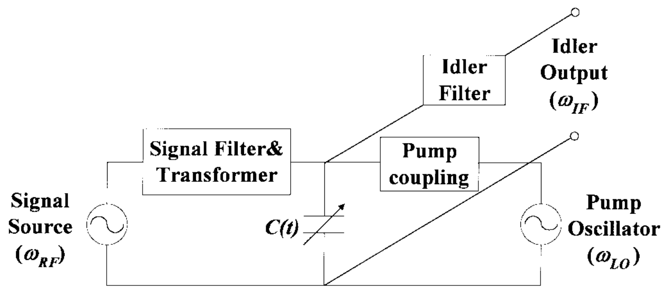



Fig. 2. Schematic diagram of a parametric amplifier in ring resonator structure.

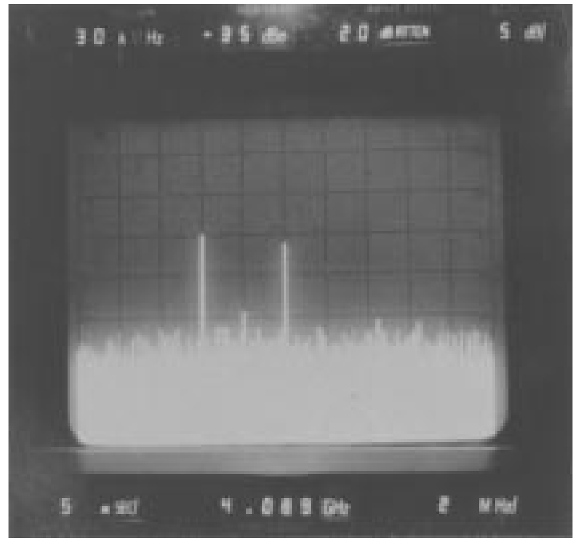
diode formed in gap region between the feedline and the ring, is connected as a common element between the signal, idler, and pump ports.

When the signal (RF) and the pump (LO) power which frequencies are near ring's resonances are applied to the circuit, the idler frequency (IF) can be extracted from the idler output port with the connection of load resistance $R_L$. If $\omega_{\mathrm{IF}} < \omega_{\mathrm{RF}}$, the circuit is known as *down-converter*, and if $\omega_{\mathrm{IF}} > \omega_{\mathrm{RF}}$, the circuit is called *up-converter*. In either case, the signal (RF) at one frequency is converted to the signal with amplification at an difference or sum frequency of RF and LO. If the pump frequency $\omega_{\mathrm{LO}}$ is chosen equal to twice the signal frequency $\omega_{\mathrm{RF}}$, the idler frequency $\omega_{\mathrm{IF}} = \omega_{\mathrm{LO}} - \omega_{\mathrm{RF}}$ is equal to the signal frequency $\omega_{\mathrm{RF}}$. In this case, the circuit is called *a degenerate parametric amplifier*. In this letter, experimental results in this mode are presented.

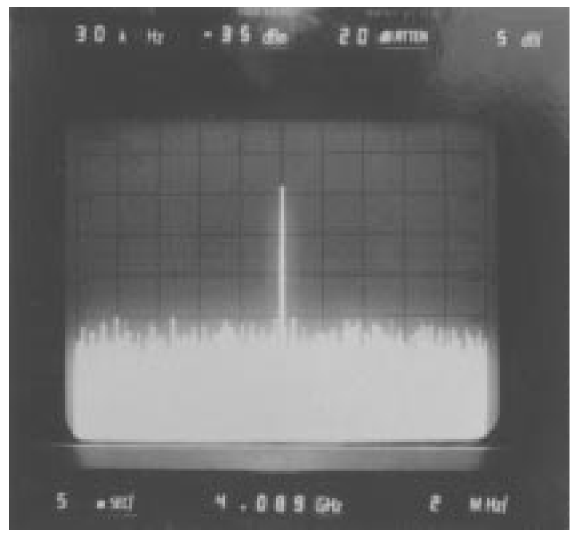
The nonlinear interaction of optical and microwave signals in a CPW-to-Slotline ring resonator was investigated using an Ortel laser diode with a lasing wavelength of 0.84 $\mu$m and a threshold current of 6.6 mA. The laser diode was biased at 15 mA and directly modulated by a HP 8340A microwave synthesized sweeper with an input power of $-10$ dBm. This intensity modulated light was focused into a coupling gap as an optical RF input signal with a bias voltage. A local microwave signal (LO) was applied to one of the feed lines via a bias-T. The output signal mixed with a optical RF input and a microwave LO was extracted from the other feed line and sent to the spectrum analyzer for the measurement.

When the RF frequency is at the ring's first resonance and the LO is at the second resonance $(\omega_{\mathrm{LO}} = 2\omega_{\mathrm{RF}})$, a mixing IF signal with $\omega_{\mathrm{IF}} = |\omega_{\mathrm{LO}} - \omega_{\mathrm{RF}}|$, can be obtained at RF frequency with an amplified output as discussed above. Fig. 3 shows the spectra for the degenerate parametric amplification effects. The RF is set to the first resonant frequency 4.09 GHz [right peak in Fig. 3(a)]. After an LO is applied at the frquency of 8.176 GHz, close to the ring's second resonance, an IF signal appears at 4.086 GHz [left peak in Fig. 3(a)]. As soon as the LO is moved to the ring's second harmonic resonance 8.18 GHz, the IF signal overlaps with the RF and an RF power amplification of 6 dB takes place at that frequency [shown in Fig. 3(b)].

We investigated the degenerate parametric amplification effects by measuring the power level of the mixing LO and RF signals as a function of applied bias voltage. The power gain, which is defined as the ratio of the power of mixing signal (LO-RF) to the power of input signal (RF), is plotted in Fig. 4. The power gain of 20 dB at zero bias could be obtained and decreased with increasing bias. The following explanation can be made about these effects. As the device bias increases, the RF power level also increases. However, the increasing rate of mixing IF power does not follow the rate of RF power increased with the applied bias voltage, even though IF power level is much higher than that of RF at a low-bias region. Therefore, the amplified signal overlapped with the optical RF and the IF has a high gain at low bias and a low gain at high bias.



(a)



(b)

Fig. 3. Spectra of degenerate parametric amplification effects. (a) LO: 8.176 GHz, IF: 4.086 GHz (left), RF: 4.09 GHz (right). (b) Amplified RF spectrum at the ring's first resonance.

These results can be compared with other similar mixing schemes of microstrip ring resonators [6], which had 7-dB gain when operated at the degenerate parametric amplification mode as a function of LO frequency (GHz) at the vicinity of the second resonance of the device. RF frequencies corresponded to first resonance were 4.09 GHz for slotline and

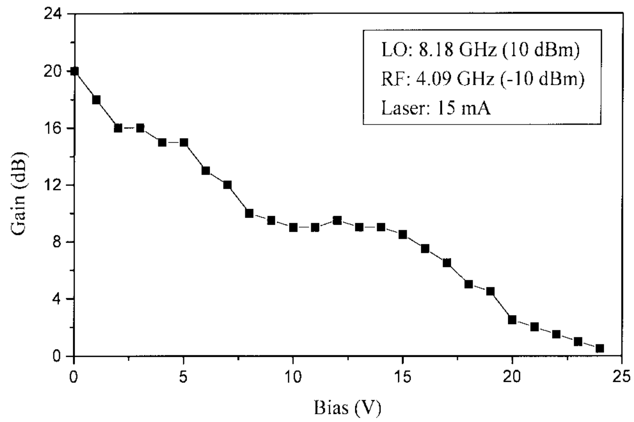



Fig. 4. Amplification gain as a function of bias.

3.512 GHz for microstrip ring resonators, respectively. RF input power to the laser diode were −10 dBm for the slotline ring and −14 dBm for the microstrip ring, respectively, while LO pump powers maintained at 10 and 22 dBm, respectively. From the figure and the data from [6], the amplification effects of RF power of the CPW-to-Slotline ring resonator at degenerate parametric amplification mode is much better than those of the microstrip ring resonator. The reason for achieving a higher gain is partly due to the new circuit arrangement.

## IV. Conclusion

A novel CPW-to-Slotline ring resonator has been introduced, fabricated on semi-insulating GaAs substrate, and characterized with excitation by a modulated optical carrier. A nonlinear interaction between an optically modulated RF input and a microwave LO has been carried out and a power gain of 20 dB without any bias could be obtained due to nonlinear parametric amplification effects. This RF amplification performance of the slotline ring resonator was much better than that of the microstrip ring resonator when operated at the degenerate parametric amplification mode. This CPW-to-Slotline ring resonator can be applied to mixers, frequency converters, and heterodyne receivers in fiber-optic links.

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