# Nonlinear Microwave Performance of an Optoelectronic CPW-to-Slotline Ring Resonator on GaAs Substrate

Jong-Chul Lee

## Abstract

A nonlinear optical-microwave interaction is carried out in an uniplanar CPW-to-Slotline ring resonator on the semi-insulating GaAs substrate, in which a Schottky photodetector is monolithically integrated as a coupling gap. When the capacitive reactance of the detector is modulated, the parametric amplification effect of the mixer occurs. In this device structure, the parametric amplification gain of 20 dB without the applied bias in RF signal is obtained. This microwave optoelectronic mixer can be used in the fiber-optic communication link.

## 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[1-3]. As a microwave-optoelectronic mixer, several attempts of microstrip ring structure have been made on the semi-insulating GaAs substrate[4, 5]. Using a Schottky detector as a nonlinear monolithic integrated circuit element into the structure, a significant power gain of the RF signal modulated by optical excitation could be obtained through the mixing with local microwave signals provided by a microwave synthesizer. Even though the microstrip is the most popular planar transmission line, other uniplanar transmission lines such as the coplanar waveguide (CPW), the coplanar strips (CPS), and the slotline are alternatives to microstrips in microwave and millimeter-wave hybrid and monolithic integrated circuits[6]. In earlier work, the optical-microwave mixing performance of a CPW-to-Slotline ring resonator on the GaAs substrate was demonstrated using optical excitation[7].

In this paper, the experimental results on nonlinear performance of an optoelectronic microwave CPW-to-Slotline ring resonator are presented, in which a Schottky photodetector is monolithically integrated at a coupling gap between the CPW feed lines and the slotline ring resonator. Using the capacitance of the Schottky detector as a time-varying reactance, the parametric amplifier in this ring structure is modeled, and the experimental results on the degenerate mode are presented and discussed.

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## 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 μm wide conductor strip and a 305 μm wide gap between the signal and the ground. The Slotline ring has an inner and outer radii of 5.555 mm and 5.615 mm, respectively. The coupling gap is designed to be 5 μm 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 CPW-to-Slotline ring resonator was fabricated using the AZ5214 double-spin image reversal photolithography, in which the photoresist profile with the thickness of about 2.7 μm for the device pattern was formed by the repeated spin coat and soft

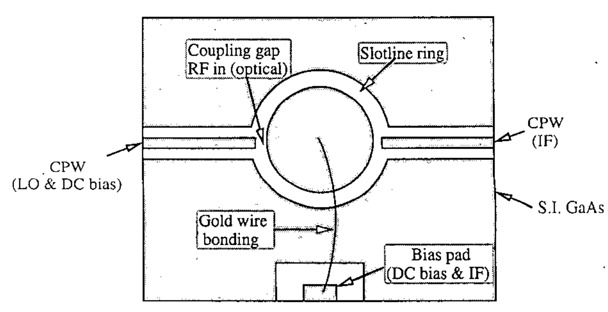



Fig. 1. The structure of the CPW-to-Slotline ring resonator.

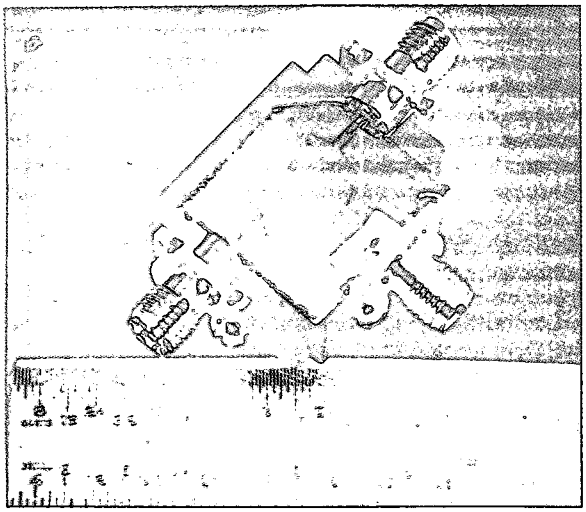


Fig. 2. Photograph of the CPW-to-Slotline ring resonator with the test fixture.

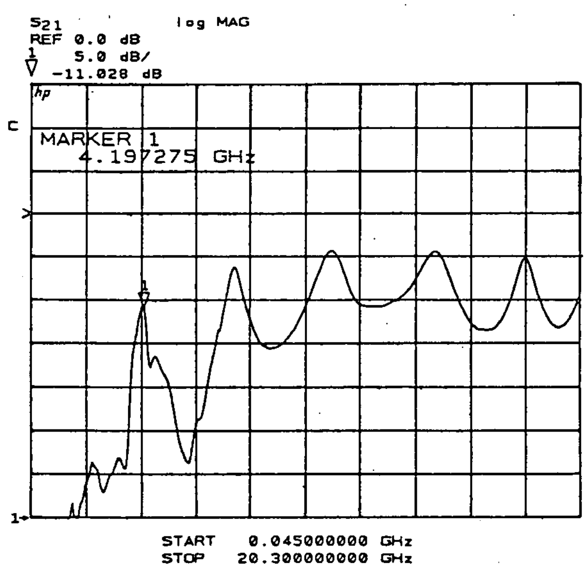



Fig. 3. Microwave $S_{21}$ characteristic of the device.

bake on a hot plate. Then, multilayer metals with a total thickness of about 2.3 μm were deposited by e-beam evaporation through the slots in the photolithographic patterns. Au/Ge and Ni were deposited as a first layer followed by the thin Au layer. Cu was chosen as a conducting metal layer because of its high conductivity and low cost compared to Au. A thin Au layer was deposited on top of the Cu layer for gold wire bonding. In addition, Ti was used as a diffusion barrier between Cu and Au. Following the conventional lift-off process using acetone, the desired metal pattern was obtained.

The device was mounted in a test fixture for experiments and SMA connectors were attached to the CPW feedlines and the bias pad as shown in Fig. 2. Gold wire bonding was carried out between the center of the ring and the bias pad by applying external bias voltage to the device. Since this device doesnt have to have back-metalization due to its unilateral structure while it usually needs in the microstrip circuit, a Delrin block, which is the insulating fixture was chosen as a mounting substrate. Fig. 3 shows the microwave $S_{21}$ parameter of the device which was measured by a HP 8510B network analyzer and the first three resonant frequencies of the device were found to be 4.19, 7.95, and 11.4 *GHz*, respectively. The corresponding insertion losses were -11, -5.1, and -4.5 *dB*, respectively. Due to the effects of coupling gaps and dispersion, the resonant harmonics are deviated from the exact values of multiple times of the fundamental resonant frequency[7].

## 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. 4 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 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 the operating frequency range. *C(t)*, the time-varying capacitance, which comes from a Schottky diode formed in the 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 the rings 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 $\omega_{IF} < \omega_{RF}$, the circuit is known as "*down-converter*," and if $\omega_{IF} > \omega_{RF}$, the circuit is called "*up-converter*." In either case, the signal(RF) at one frequency is converted to the signal with amplification at a difference or sum frequency of RF and LO. If the pump frequency $\omega_{LO}$ is chosen equal to twice the signal frequency $\omega_{RF}$, the idler frequency

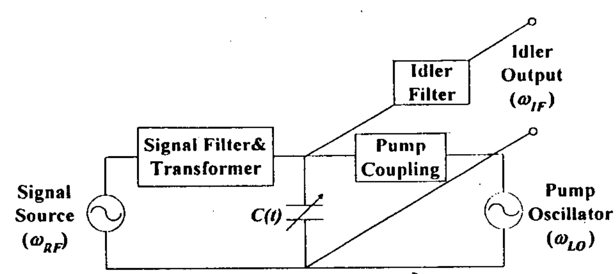



Fig. 4. Schematic diagram of a parametric amplifier in ring resonator structure.

$\omega_{IF} = \omega_{LO} - \omega_{RF}$ is equal to the signal frequency $\omega_{RF}$. In this case, the circuit is called "*a degenerate parametric amplifier.*" In this paper, 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 the experimetal setup shown in Fig. 5. Here, as a light source, an Ortel laser diode with a lasing wavelength of 0.84 $\mu m$ and a threshold current of 6.6 *mA* was used. 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 rings first resonance and the LO is at the second resonance($\omega_{LO} = 2\omega_{RF}$), a mixing IF signal with $\omega_{IF} = |\omega_{LO} - \omega_{RF}|$, can be obtained at the RF frequency with an amplified output as discussed above. Fig. 6 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. 6.a). After an LO is applied at the frquency of 8.176 *GHz*, close to the rings second resonance, an IF signal appears at 4.086 *GHz*(left peak in Fig. 6.a). As soon as the LO is moved to the rings 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 as Fig. 6.b.

The degenerate parametric amplification effects were investigated 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. 7. The power gain of 20 *dB* at zero bias could be obtained and decreased with increasing bias. These results can be compared with other similar mixing schemes of the microstrip ring resonator[5], which had a 7 *dB* gain when operated at the degenerate parametric amplifi

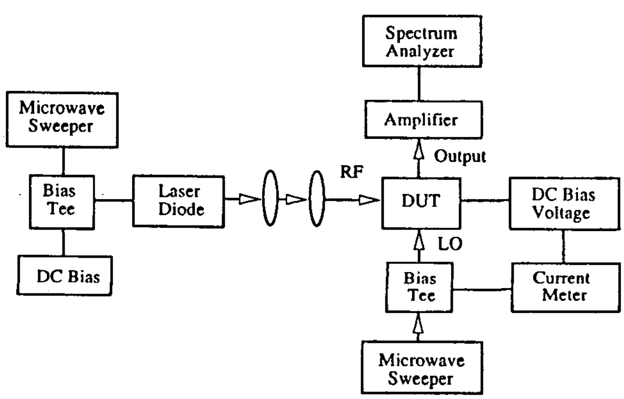
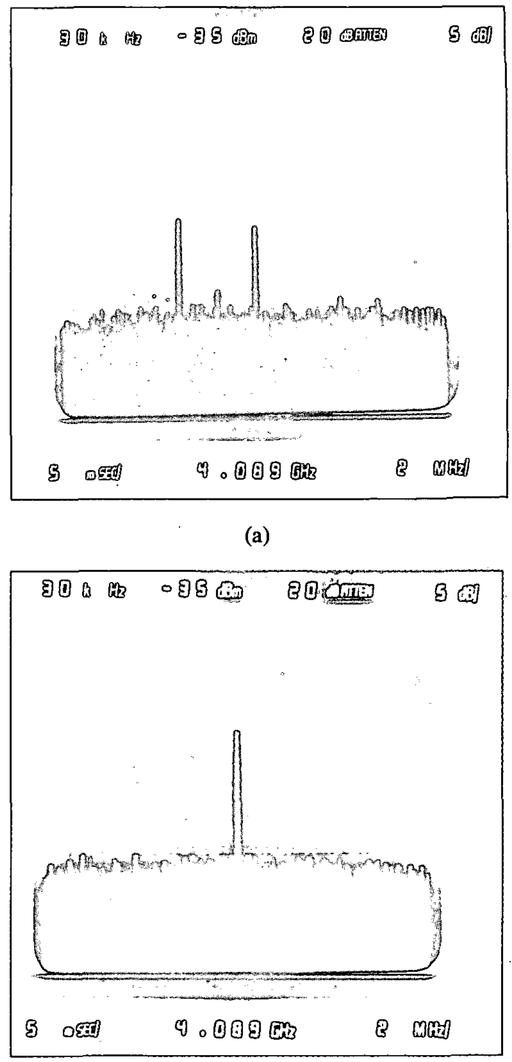



**Fig. 5.** The experimental set up for optical excitation.



(a)

(b)

**Fig. 6.** 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 rings first resonance

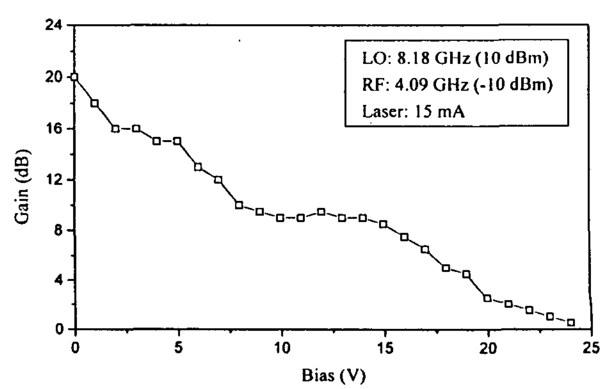



**Fig. 7.** Amplification gain as a function of bias.

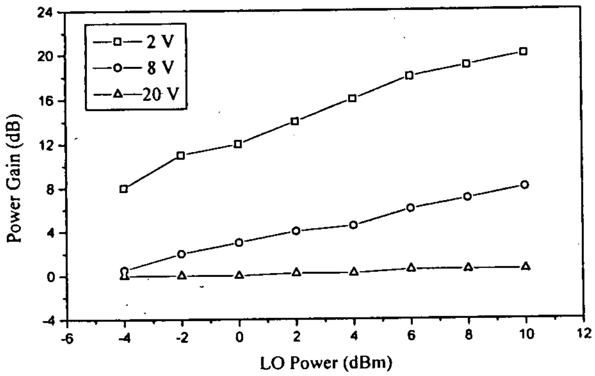



**Fig. 8.** Power gain as functions of device bias and LO pumping power.

cation mode as a function of the 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, 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 *dBm* and 22 *dBm*, respectively. From the figure and the data from ref. 5, the amplification effects of RF power of the CPW-to-Slotline ring resonator at the degerate parametric amplification mode is much better than those of the microstrip ring resonator.

Also, this power gain was investigated as functions of the LO pumping power and bias level, which is shown in Fig. 8. The power gain due to nonlinear parametric amplification effects increases in proportion to the LO pumping power for the low bias condition. With an LO pumping power of 10 dBm and an RF input power of -5 *dBm*, an RF power gain of more than 20 *dB* can be obtained. The power gain reduces with increasing bias and becomes almost zero at 20 *V*. 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 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 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.

## IV. Conclusions

A novel CPW-to-Slotline ring resonator has been introduced, fabricated on the 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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