40 GHz Quasi-Optical Second Harmonic Spatial Power Combiner Using FETs and Slots

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ABSTRACT

FET oscillators integrated with slot radiators are used for constructing quasi-optical second harmonic spatial power combiners. Double-oscillator power combiner circuits with a strongly coupled structure generated the 40 GHz second harmonic frequencies. The radiation patterns of the double-oscillator power combiners are also discussed.

INTRODUCTION

The quasi-optical power combiner is attractive to obtain high power from solid-state devices, either diodes or FETs[1-4]. These combiners are made of radiators and circuits which are integtated and are often inseparable. It was demonstrated that a slot antenna in the circuit ground plane increases design flexibility since both sides of the substrate can be effectively used[5]. Due to its high DC-RF conversion efficience, FET power combiners are preferred[6]. However, all these works operate at microwave frequencies. In order to generate a millimeter-wave signal, it is useful to use the second harmonic[3],[4].

This paper reports new quasi-optical FET second harmonic spatial power combiners generating around 40 GHz with a direct coupling between oscillators through a microstrip line. Use of FETs and completely planar structure makes the prototype circuit amendable to monolithic integration at millimeter-wave frequencies.

DESIGN

In order to combine the second harmonic signals generated from FETs, we considered a circuit configuration with negative resistance oscillators and a slot array in the E-plane. Advantages of such configuration are as follows. The negative resistance oscillator has a simple configuration, while the separation of the slots in the E-plane array can be reduced to form a more compact structure. For this purpose, a single oscillator with two slots is investigated as a unit cell for a combiner circuit configuration made of multi-oscillators with a multi-slot array. Next, we designed the double oscillators with multi-slots. The antenna patterns of the second harmonic power combiner should be designed to spatially separate the desired signal from the fundamental power. For instance, the second harmonic power should be effectively added up (Σ pattern), while the fundamental power is cancelled (Δ pattern) in a certain (typically, a broadside) direction. Design of such an array requires appropriate phase relationships in the direction of interest, such as the broadside direction, for both the fundamental and the second harmonic.

i) Single Oscillator (Structure 1)

Figure 1 shows the single-oscillator circuit configuration with two slots. Each slot has the length of $1\lambda_1$ (where λ_1 indicates the wavelength for the fundamental frequency) and the width of $0.08\lambda_1$. Since this one-wavelength slot antenna with a center feed provides 50 Ω load to the circuit, the oscillator was designed to have an impedance of -50 Ω. As two 50 Ω loads are connected in parallel with the oscillator feed line, one-stage quarter-wavelength transformers were used between the antenna and the oscillator feed line. The characteristic impedances of those feed lines are indicated using Z_0 (=50 Ω) in Figure 1. The separation of the two slots is $\lambda_1/2$. The expected second harmonic in-phase condition is also shown in Figure 1.

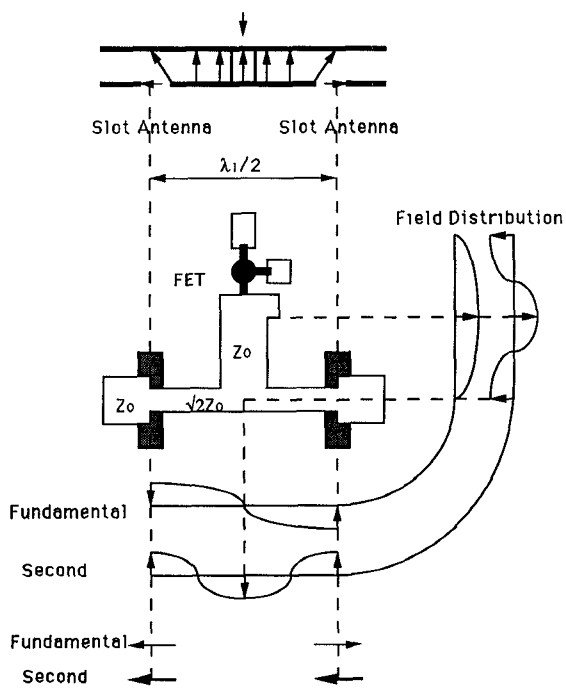

Fig. 1 Single-oscillator with two slots (Structure 1)

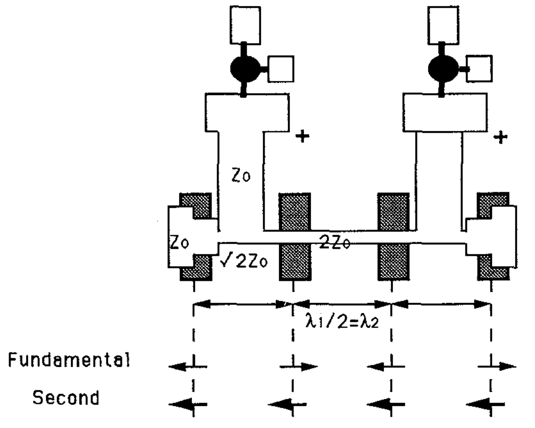

Fig. 2 Double-oscillator with four slots (Structure 2)

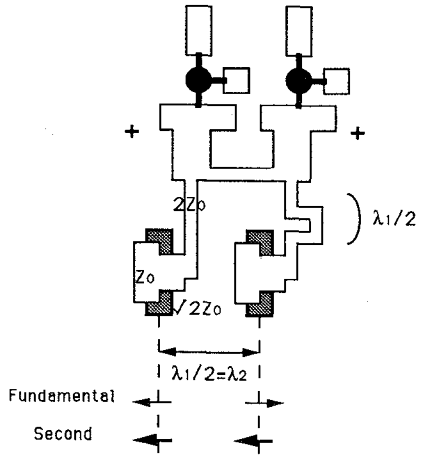

Fig. 3 Double-oscillator with two slots (Structure 3)

ii) Double Oscillators

a) Four-Slot Structure (Structure 2)

In order to gain knowledge of the single oscillator configuration in a larger array with least modification, we designed the double-oscillator circuit with four slots as shown in Figure 2. Each slot has the length of $1\lambda_2$ (where λ_2 indicates the wavelength for the second harmonic frequency) and the width of $0.08\lambda_2$. In this case, the impedance matching conditions are considered at the second harmonic. Each oscillator has -50 Ω input impedance and the slots are separated by $\lambda_1/2(=\lambda_2)$. To satisfy the requirement on the antenna patterns, the phase relationships on the slots must be as shown in Figure 2 under the in-phase condition (which indicates +,+ in the figure) between the two oscillators.

b) Two-Slot Structure (Structure 3)

In order to increase the packaging density, we made the circuit of double oscillators with two slots. The double-oscillator configuration with two slots is shown in Figure 3. The impedance matching conditions, the separation of the two slots and slot-length and slot-width are identical to those of the double oscillators with four slots reported above. However, in this case, slots are not on the coupling line between the double oscillators but on the open circuited line. In addition, one of these open lines has an additional $\lambda_1/2$ length in order to make the phase on the slot inverted at the fundamental frequency but remained in-phase at the second harmonic frequency.

EXPERIMENTAL RESULTS

i) Operating Frequencies and Tuning Ranges

An observed spectrum of the second harmonic of a single oscillator with two slots (Structure 1) is shown in Figure 4. This oscillator has the 19.15 GHz fundamental frequency and the 37.43 GHz second harmonic frequency.

The power combiners (Structures 2 and 3) generated fundamental signal at about 19 GHz and second harmonic signal at about 39 GHz with a stable locking status.

As one of the important parameters of an oscillator, the tuning range was investigated. The double oscillators with two slots had wider tuning range than those with four slots. This results may be explained from the fact that the periodic series-loads of slots provide a higher external Q which is inversely proportional to the tuning frequency range. The operating frequencies and the tuning ranges of these circuits are summarized in Table 1.

Table 1 : Operating Frequency and Tuning Range

	Operating Frequency	Tuning Range
Single-Two	19.35 GHz	61 MHz
Double-Four	19.32 GHz / 40.50 GHz	223 MHz
Double-Two	19.36 GHz / 37.80 GHz	377 MHz

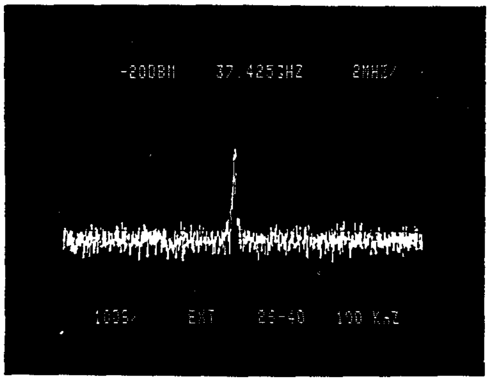

Fig. 4 The spectrum of the second harmonic frequency

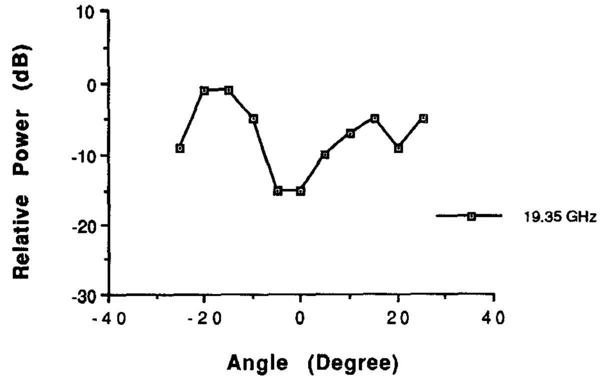

Fig. 5 Quasi-Optical Oscillator Antenna Pattern (Single oscillator - 2 slots)

ii) Radiation Patterns

The obtained radiation pattern in the E-plane of the single oscillator with two slots is shown with Δ pattern in Figure 5.

The radiation patterns of Structure 2 are shown in Figure 6 which indicates the Δ pattern for the fundamental and the Σ pattern for the second harmonic. Therefore, we can conclude that two oscillators are in the in-phase condition at the fundamental frequency. Next, the effective radiated power (ERP) is derived. According to the experimental date from the 10 GHz slot antenna[6], its average gain is 3 dBi. Assuming this gain is maintained at 40 GHz, we find that the ERP of this circuit is 31.6 dBm.

Higher levels of radiations toward ±40 degrees are due to deficits of experimental setup.

The radiation patterns of Structure 3 are shown in Figure 7. It is clear that this two-slot circuit meet our purpose. The ERP is found to be 35.7 dBm.

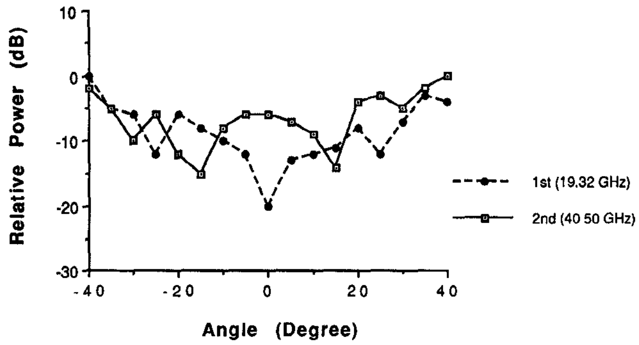

Fig. 6 Quasi-Optical Oscillator Antenna Pattern (Double oscillators - 4 slots)

CONCLUSIONS

Using the package type FETs, we obtained stable second harmonic spatial power combiners at 40 GHz with oscillators coupled through a microstrip line. The circuits consist of FET oscillators and slot antennas. Through the obtained antenna patterns, we can also find the information of the phase relationship between the oscillators. By controlling the phases on the slots, we obtained the Δ pattern for the 19 GHz fundamental and the Σ pattern for the 40 GHz second harmonic.

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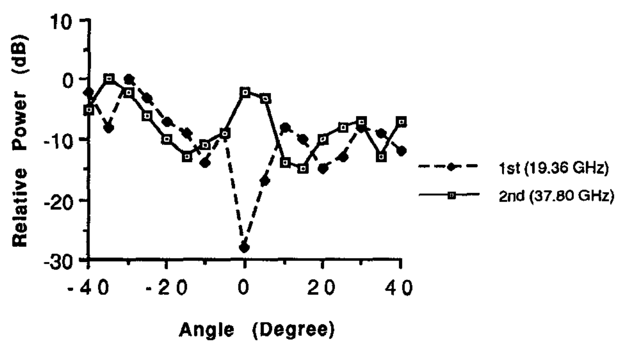

Fig. 7 Quasi-Optical Oscillator Antenna Pattern (Double oscillators - 2 slots)

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