High Effective Subharmonic Injection Locking of a Millimeter-Wave IMPATT Oscillator

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Abstract—**Effective stabilization of an IMPATT oscillator in the millimeter-wave region can be achieved through subharmonic injection locking to a weak parasitic oscillating signal. In subharmonic injection-locking experiments more than 19 dB of locking gain at 10-MHz locking range was obtained at a subharmonic ratio 1:2 of the main oscillating frequency. At the subharmonics 1:4 and 1:6, the locking gain was more than 12 and 13 dB at 10 MHz, respectively.**

Using the parasitic oscillating signal, higher than 32-dB gain and 10-MHz locking range at a subharmonic ratio 1:2 of the parasitic oscillating frequency was obtained. This locking gain was 13 dB higher than that for the main oscillating signal. At the subharmonic ratio 1:4, the gain was more than 15 dB higher. As measured with the spectrum analyzer, the oscillating signal which was locked by the subharmonic injection signal almost coincided with the injection signal. These data show that the subharmonic injection locking has high gain as compared with that using the main oscillating signal.

I. Introduction

One of the methods for stabilizing a millimeter-wave IMPATT oscillator is the phase locking method using an external highly stable injection signal. If a crystal oscillator, which is commonly used as a highly stable signal source, is used to generate an original locking signal, a highly stable locked oscillator will be realized. However, high-order frequency multipling circuits will be necessary for a millimeter wave oscillator. The IMPATT oscillator, however, has itself a frequency multipling function [1]–[5], and its free-running oscillating signal can be locked by a subharmonic frequency. If subharmonic injection locking [6] is more effective than other methods, it is especially useful for millimeter-wave oscillators. The frequency multipling circuits are simplified and can be small in size and light in weight.

In an IMPATT oscillator, the parasitic oscillating signals in free-running oscillation need to be suppressed as much as possible in order to obtain high efficiency. However, in many cases, some weak parasitic oscillations are observed. The free-running main oscillating signal and the parasitic signals are locked to each other when a locking signal is injected into either the parasitic oscillating signal or the main oscillating signal.

We have applied this fact to stabilize the IMPATT oscillator [7]. Effective stabilization was realized through subharmonic injection locking to a weak parasitic oscillating signal in the millimeter-wave region. In this paper some experimental data obtained regarding phase locking performance of IMPATT oscillators at 34.13 GHz and their characteristics are presented.

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II. Experimental Circuit Construction

The outline of the experimental circuit is shown in Fig. 1. The experimental circuit is composed of an IMPATT diode mount, an injection-locking signal circuit for the main oscillating signal, a subharmonic injection-locking signal circuit and an output signal measuring circuit. The waveguide used in the millimeter-wave circuits is a WJ-320 rectangular waveguide.

A. IMPATT Diode Mount

The IMPATT diode is mounted across a reduced-height waveguide in a brass block. The oscillating frequency is adjusted with a short plunger which is provided at the end of a reduced-height waveguide. The dc bias is supplied with a semiridged coaxial cable, and the circuit is shorted at the high frequencies by a capacitive element. In addition, a loosely coupled cavity (coupling constant = 0.05, $Q_L = 800$) is provided at the IMPATT mount in order to adjust the frequency of the parasitic oscillation over a 3-GHz range.

The injection-locking signal for the main oscillation is fed through the circulator in the millimeter-wave circuit. The subharmonic injection-locking signal is fed to the IMPATT diode from the dc bias circuit through a dc blocking element.

B. Injection-Locking Signal Circuits

The injection-locking signals are fed from a BWO sweep generator, and the output power is stabilized to less than 0.2 dB with automatic level control circuits. The subharmonic injection signal is filtered by a low-pass filter and fed into the IMPATT diode through a coaxial cable. In addition, the low-pass filter acts like a reflector for higher frequencies than the cutoff frequency, so that the subharmonic circuit of the injection signal is not influenced by the oscillating signal of the IMPATT diode.

The input power of the injection-locking signals were measured at points A and B in Fig. 1.

III. Experimental Results

A. Subharmonic Injection-Locking Characteristics Using the Main Oscillating Signal

The IMPATT diode used in these experiments is a CW Si-IMPATT diode (Model A 3805-SH Hughes). The ex-

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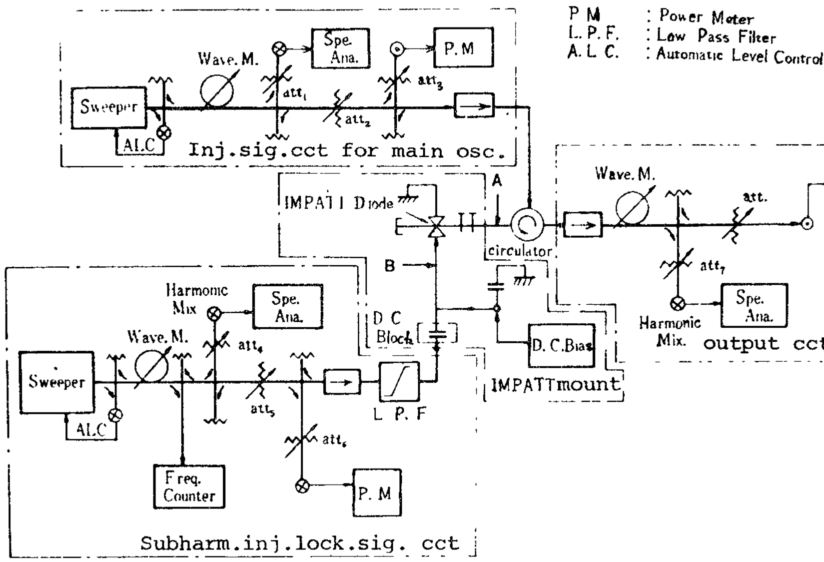

Fig. 1. Experimental circuit construction.

perimental work has been performed with the IMPATT diode mounted in a waveguide. At 140-mA bias current, the IMPATT oscillator is tuned to a frequency of 34.13 GHz and matched for an optimum power output of 11.5 dBm. In this case, the parasitic oscillating signal level is more than −20 dB down from the main oscillating signal level.

Fig. 2 shows the subharmonic injection-locking characteristics for the main oscillating signal at 34.13 GHz. The locking ranges are indicated by the length between the upper and lower curves at a locking input power indicated by the abscissa. The parameters are the subharmonic ratio of $1:n$. Maximum locking ranges for subharmonic injection are less than those observed when there is direct frequency locking (1 : 1 characteristic), and they decrease with increasing ratio. The dotted line in Fig. 2(a) shows the frequency deviation of the center oscillating frequency, which increases as the injecting power increases and as the subharmonical ratio decreases. The deviation of locking output power is shown by the minimum and maximum values in Fig. 2(b). In general, these deviations were less than about 0.5 dB in the locking range.

In operating the IMPATT oscillator, it is very difficult to estimate the actual power injecting into the diode. The injecting power for locking in Fig. 2 corresponds to the measured values at points A and B in Fig. 1 when the diode was not operating. Accordingly, the mismatch loss is included in those values. It was very difficult to match the coaxial circuit for the subharmonic injection signal in the IMPATT operating condition. The dc resistance of the IMPATT diode was about 160 Ω (23 V/140 mA) in free-running oscillation. The subharmonic injection signal circuit was matched to the dc resistance. In order to separate out the mismatch loss, we measured the return loss of the injection signal circuit. We would not measure the return loss accurately because signals below the cutoff

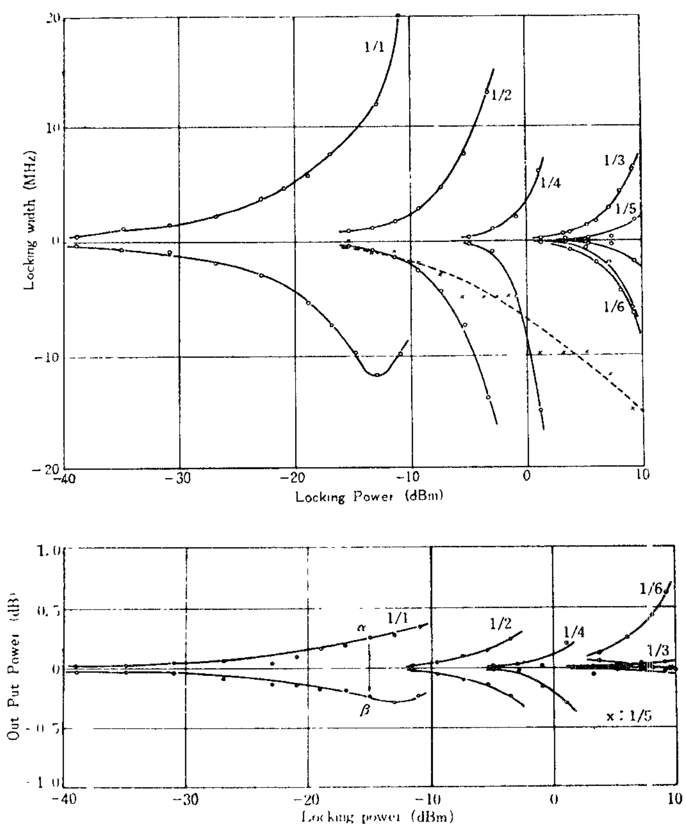

Fig. 2. Subharmonic injection-locking characteristics for main oscillating signal of 34.13 GHz. (a) Locking width versus injection power for locking. (b) Locking output power variation (max and min). (Parameter $(1/n)$: subharmonic ratio. 0 values of each axis: free running condition).

frequency of the low-pass filter were generated by the IMPATT oscillator and returned to the injection signal circuit. In cases where the subharmonic ratio is odd, the efficiency was not good, but with an even number we obtained good locking gain characteristics.

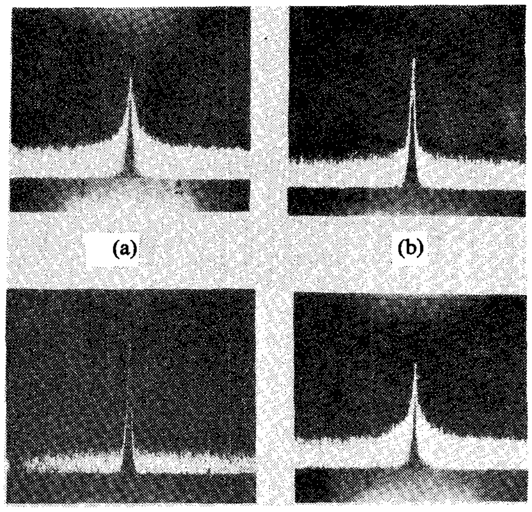

Fig. 3. Spectrum for injection signal and for locked output signal. (a) Free-running oscillating signal (34.13 GHz). (b) Injection signal (5.7 GHz). (c) 34.13-GHz signal locked to 34.13/2-GHz injection signal. (d) 34.13-GHz signal locked to 34.13/6-GHz injection signal.

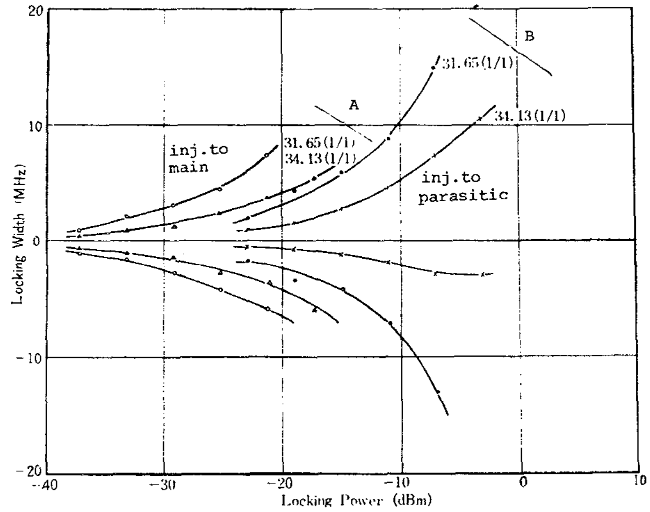

Fig. 4. Correlation between main oscillating signal and 31.65-GHz parasitic oscillating signal A when locking signal was injected into 34.13-GHz signal, B when locking signal was injected into, 31.65-GHz signal. (34.13-GHz main oscillating signal, 31.65-GHz parasitic oscillating signal.)

34.13-GHz output spectra are shown in Fig. 3. Fig. 3(a) and (b) shows the spectrum of the free-running oscillating signal and the subharmonic injection signal, respectively. Fig. 3(c) and (d) shows the spectrum obtained when the injection frequencies were 8.53 and 5.7 GHz. The spectra were observed with subharmonic ratios of 4 and 6. Their observed spectra are similar to those observed by others for 1 : 1 injection locking, but they exhibit larger sidebands as the subharmonic ratio decreases. The locking signal power which is converted from the subharmonic frequency to the main oscillating frequency decreases as the subharmonic ratio increases. This condition corresponds to the high locking gain condition. As shown in [8] and [9], the FM and AM noise in the sidebands of the oscillating signal increase as the locking gain increases in direct frequency locking. It appears that the subharmonic injection-locking mechanism is essentially the same as in direct frequency locking. For a 10-MHz locking range, more than 19 dB of locking gain was obtained at a subharmonic ratio of 1 : 2. At subharmonic ratios, 1 : 4 and 1 : 6, more than 12- and 13-dB locking gains were obtained, respectively.

B. Correlation Between the Main Oscillating Signal and a Parasitic Oscillating Signal

In general, since the IMPATT diode oscillator operates with a low external Q (less than 100), and the loaded Q (Q_L) is very small, the oscillating range is very wide and weak parasitic oscillations are frequently observed. In our experiments, many parasitic oscillations were observed. They were very difficult to measure directly, however, because their levels were comparable to the measurement system noise. To observe the parasitic oscillating signals, we used the fact that the main oscillating signal and the parasitic oscillating signal were affected by the external injection signal at the same time. In this method, many parasitic oscillating signals which have very small output level were observed and shown in Table I with expected locking frequencies.

TABLE I
MAIN OSCILLATING FREQUENCY (M), PARASITIC OSCILLATING FREQUENCIES (P), EXPECTED SUBHARMONIC FREQUENCIES, AND * OBSERVED INJECTION LOCKED FREQUENCIES

Free Run. Freq. (GHz)	Locking Freq. (GHz)				
1/1	1/2	1/3	1/4	1/5	1/n n: Mult.No.
40.22 (P)	20.11	13.41*	10.06	8.04*	
36.61*(P)	18.31*	12.20*	9.15*	7.32	
35.37*(P)	17.69*	11.79	8.84*	7.07	
35.02*(P)	17.51*	11.67	8.76*	7.00	
34.13*(M)	17.07*	11.38*	8.53*	6.83	
33.27*(P)	16.64*	11.09*	8.32*	6.65	
32.93*(P)	16.47*	10.98*	8.23*	6.59	
31.65*(P)	15.83*	10.55*	7.91*	6.33	
38.08 (P)	14.04	9.36*	7.02	5.62	

Fig. 4 shows an example of the correlation, for direct locking, between the main oscillating signal (34.13 GHz) and the parasitic oscillating signal which was the directly observable signal (31.65 GHz, −8-dBm output). Fig. 4 also shows that the main and parasitic oscillating signal are locked at the same time by each injection signal. Where A in Fig. 4 shows the characteristics for injecting

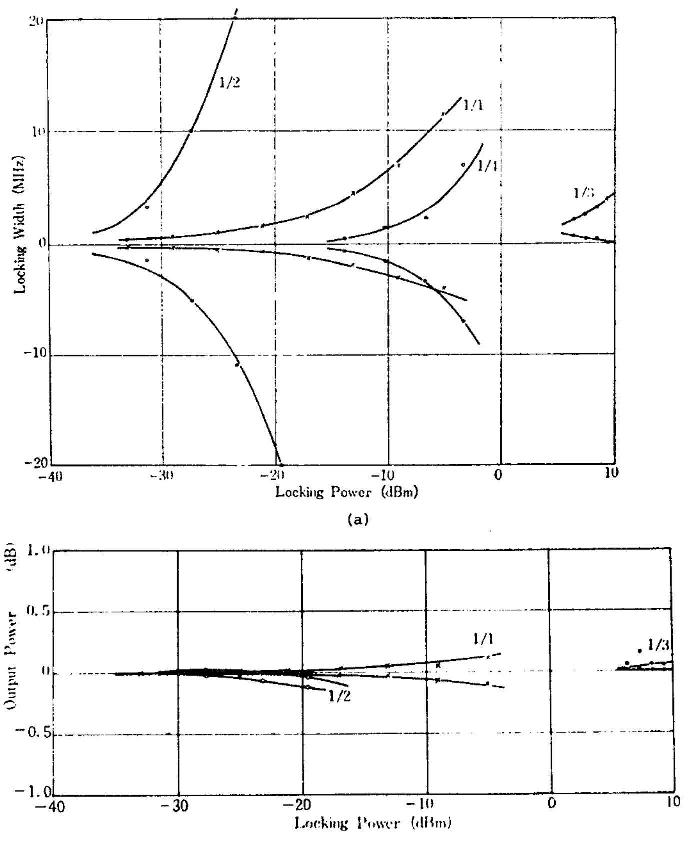

Fig. 5. Subharmonic injection locking characteristics for 31.65-GHz parasitic oscillation. (a) Locking width versus injection power for locking. (b) Locking output power variation (max. and min.). (1 : *n* subharmonic ratio, 0 values of each axis: free-running condition.)

the locking signal to the main oscillating signal, *B* is for injecting to the parasitic one.

The parasitic signal has a wider locking range at the same locking signal level than that of the main oscillation. These observations indicate that the parasitic oscillating signal is more sensitive to the injection signal than the main oscillating signal.

C. Subharmonic Injection Locking to a Parasitic Oscillating Signal

Table I shows the subharmonic injection-locking frequency expected. *M* and *P* in Table I indicate the main or parasitic oscillating frequencies, respectively. Fig. 5 shows, as an example, the characteristic of the main oscillating signal which is locked using the 31.65-GHz parasitic oscillation. The subharmonic locking signal was locked to the 31.65-GHz signal and the characteristic was measured at the output frequency of 34.13 GHz.

Fig. 5(a) shows the locking range for injection power as frequencies. Fig. 5(b) shows the locked output power variation, and the upper and lower curves show the power over the range of locking. The locking conditions were observed on the spectrum analyzer (HP-141T). When a subharmonic frequency of a parasitic oscillation is injected into the IMPATT diode oscillator, the frequency of the main oscillating signal deviates with the variation of

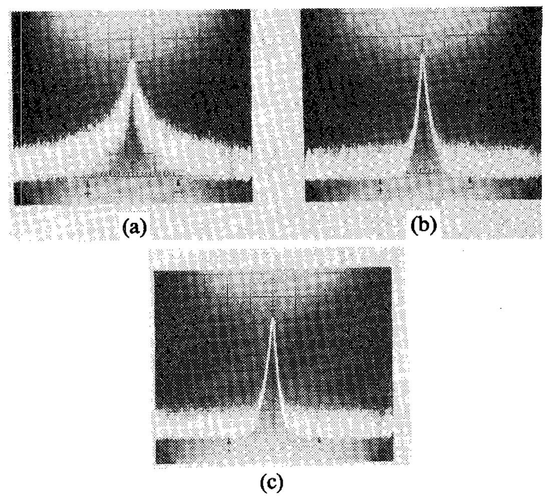

Fig. 6. Spectrum of subharmonically locked IMPATT diode oscillating signal. (a) Free-running oscillating signal (34.13 GHz). (b) Injection signal (31.65/4 GHz). (c) 34.13-GHz signal locked to 31.65/4-GHz injection signal.

the injection signal frequency. If the injection signal frequencies are out of the locking range, the main oscillating signal becomes free running. We checked for locking using this criteria. Fig. 5 shows the poor locking characteristics for the odd subharmonic ratio and good locking characteristics for even ratios.

It is interesting that the main oscillating signal is more easily locked by subharmonic injection at the parasitic oscillation frequence than the direct locking. In the case of subharmonic ratio 1 : 2, especially, the locking range and locking gain were wider and higher than those for the direct locking. This shows that the subharmonic injection-locking method using a parasitic oscillation is a very effective method for stabilizing IMPATT diode oscillators. At 10-MHz locking range, locking gain higher than 32 dB at a subharmonic ratio of 1 : 2 was obtained. At the subharmonic ratio 1 : 4, it was more than 15 dB for a 10-MHz locking range.

The spectrum of a subharmonically locked signal (34.13 GHz) when a locking signal (7.9 GHz, subharmonic ratio 1 : 4) was injected into the 31.65-GHz parasitic oscillating signal is shown in Fig. 6. We also obtained similar characteristics with the other parasitic oscillating signals. However, the spectrum of the locked output signal became noisier as the parasitic oscillating power decreased.

D. Summary of the Experimental Results

Fig. 7 shows the characteristics for subharmonic injection locking of the principal parasitic oscillation. The abscissa shows the locking range (in megahertz), and the ordinate shows the power ratio, i.e., the subharmonic injection power normalized by the required power for direct locking (at 34.13 GHz). These characteristics show that, at a subharmonic ratio of 1 : 2, the 31.65- and 36.61-GHz parasitic oscillation signals are stabilized at a lower input locking signal (34.13 GHz). The locking characteristic for 31.65 GHz at a subharmonic frequency ratio of 1 : 4

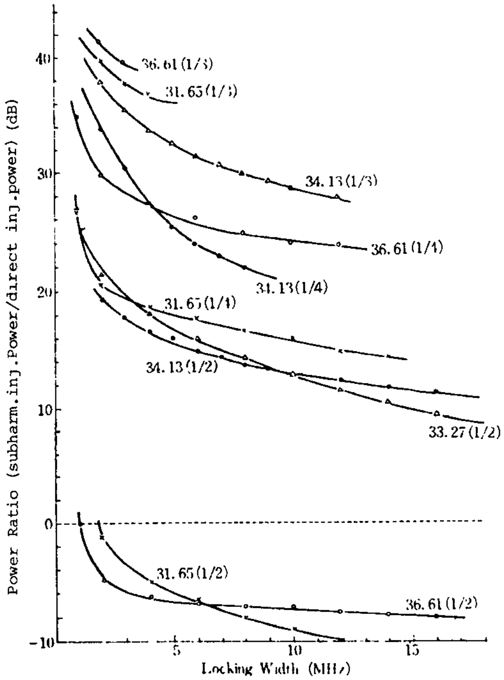

Fig. 7. Characteristics for subharmonic injection locking of principal parasitic oscillation. Abscissa: locking range (MHz). Ordinate: subharmonic injection power normalized by the power for 34.13-GHz direct locking (dB).

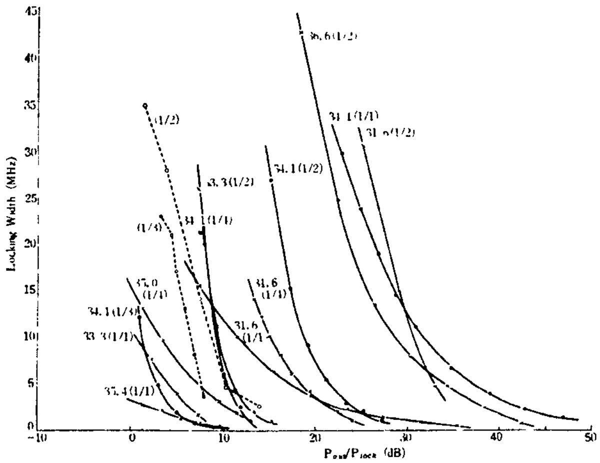

Fig. 8. Characteristics of locking versus locking gain. (Dotted lines show the data of [6].)

is comparable with that of the 34.13-GHz main oscillation at the ratio of 1 : 2.

Fig. 8 is a plot of locking range versus locking gain. The latter is the ratio of 34.13-GHz output power to the injection power at the injection frequency.

In order to compare with the other experimental data [6], the data which were obtained with CW GaAs microwave Gunn-diode oscillators is shown by the dotted line. Very little experimental data are available for subharmonic injection locking.

IV. Conclusion

The following facts become clear after the investigation of the subharmonic injection locking:

1) The weak parasitic oscillating signal which is attendant with the main oscillation signal can be observed by using the locking behavior of the main oscillation signal, and the power can be measured by calibrating the locking characteristics.

2) When the locking signal is injected into the main oscillating signal or the parasitic oscillating signal, both signals show locking action at the same time, and the locking range and the locking gain for that of the parasitic oscillating signal is broader and higher than those of the main oscillating signal.

3) Subharmonic injection locking using the parasitic oscillating signal is very useful. High efficiency is obtained at the subharmonic ratio of 1 : 2. It is very difficult to intentionally control the power and frequency of the parasitic oscillations in waveguide diode mounts in the millimeter-wave region. For the purpose of adjusting the parasitic oscillations, we applied a loose coupling, low-Q cavity near the IMPATT diode mount.

Practical oscillators using subharmonical injection locking can be realized using Si-IMPATT diode oscillators in the millimeter-wave region, although further investigation is needed.

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References

[1] T. P. Lee and R. D. Standley, "Frequency modulation of a millimeter-wave IMPATT diode oscillator and related harmonic generation effect," *Bell Syst. Tech. J.*, vol. 48, no. 1, pp. 143–161, Jan. 1969.

[2] C. A. Bracket, "Characterization of second-harmonic effect in IMPATT diode," *Bell Syst. Tech. J.*, vol. 49, no. 10, pp. 1777–1810, Oct. 1970.

[3] M. Ohomori, H. Niizuma, and Y. Ishii, "Multiple function operations with an avalanche diode," *Trans. IECE* (Japan), vol. 54-C, no. 10, pp. 916–923, Sept. 1970.

[4] K. Mouthaan, "Nonlinear analysis of the avalanche transit-time oscillator," *IEEE Trans. Electron Devices*, vol. ED-16, p. 935, Nov. 1969.

[5] ——, "Characterization of nonlinear interaction in avalanche transit-time oscillators, frequency multipliers, and frequency dividers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 853–862, Nov. 1970.

[6] H. G. Oltman and C. H. Nonnemaker, "Subharmonically injection phase-locking Gunn oscillator experiments," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, p. 728, Sept. 1969.

[7] R. Hayashi and M. Onda, "Stabilization of an IMPATT oscillator through subharmonical injection locking to a parasitic oscillation," *Trans. IECE* (Japan), vol. 59-B, no. 12, pp. 590–591, Dec. 1972.

[8] M. Gupta, "Noise in avalanche transit-time devices," *Proc. IEEE*, vol. 59, Dec. 1971.

[9] H. Thaler, G. Ulrich, and G. Weidmann, "Noise in IMPATT diode amplifiers and oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, Aug. 1971.