Frequency-Locked GaAs/AlAs Superlattice Oscillator for Tunable Narrowband Microwave Generation

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***Abstract*—We observed frequency locking of a wide-miniband GaAs/AlAs superlattice oscillator. The oscillator showed a free self-sustained current oscillation giving rise to microwave generation (power 100 μW) at a natural frequency (near 5 GHz) and ultraharmonics. A narrowband driving field locked the oscillator and caused a drastic narrowing (from 10^6 Hz to less than 10 Hz) of the halfwidths of the microwave lines, now centered at the driving frequency and its harmonics; at a driving power of 10 μW we obtained a locking range of 1% around the natural frequency. Our experiment, performed with a superlattice integrated in a planar microwave circuit, shows that a locked superlattice oscillator is suitable for tunable narrowband generation of high-frequency radiation.**

***Index Terms*—Locked oscillators, microwave oscillators, semiconductor superlattices.**

I. Introduction

RECENTLY, it has been demonstrated that a wide-miniband GaAs/AlAs superlattice generated microwaves at a natural frequency near 7 GHz and ultraharmonics, with halfwidths of the order of 10 MHz [1]; the superlattice, with the miniband electrons carrying the current, was biased in a state of negative differential conductance. The microwave generation, connected with a self-sustained current oscillation, was attributed to traveling high-field charge density domains, with the natural frequency mainly determined by the domain velocity and the superlattice length. In this letter we will show that the current oscillation of a superlattice can be frequency-locked by an external microwave field and that the locked oscillator is frequency tunable; we performed our study with a superlattice at room temperature, which was integrated in a planar microwave circuit.

II. Experimental

Using a superlattice with 120 periods of 49-Å-thick GaAs and 13-Å-thick AlAs layers uniformly doped with silicon (concentration 1.4×10^{17} cm^{-3}), we prepared a quasi-planar superlattice electronic device (SLED) according to a recent description [2]; the SLED (Fig. 1) contained an active small-area (10 μm $\times$ 10 μm) superlattice mesa in series with a large-area superlattice mesa and had electric contacts on the top of the mesas. The SLED was integrated in a microstrip circuit. By structuring a copper film on an epoxy substrate we fabricated a 50-Ω transmission line, a low-pass filter with narrow strips in series with wide strips, and a high-pass filter in the form of an interdigital capacitor (Fig. 1). The SLED was soldered in a gap (300 μm) of the transmission line. On one side, the SLED had contact to the ground copper plane by a plated-through hole and, on the other side, to the filters. The low-pass filter was connected with a voltage source (voltage U), and the high-pass filter via a high-frequency port (microstrip-coaxial adapter) with a power splitter allowing to measure the spectrum of microwave radiation emitted from the SLED and to couple an external microwave field to the SLED. As an external microwave source we used a narrowband synthesizer, which delivered microwave radiation within a bandwidth of several hertz.

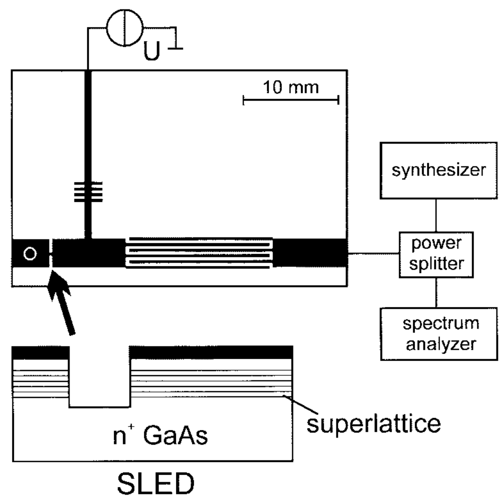

Fig. 1. Superlattice electronic device (SLED) integrated in a planar microwave circuit.

III. Results

The I–V characteristic [Fig. 2(a)] of the SLED showed a region of negative differential conductance with current jumps that were an indication for the occurrence of a self-sustained current oscillation, giving rise to microwave generation. At a fixed voltage [2.5 V, arrow in Fig. 2(a)], the microwave spectrum [Fig. 2(b)] consisted of a line at a natural frequency ν_0 (near 4.6 GHz) and ultraharmonic lines. The power at ν_0

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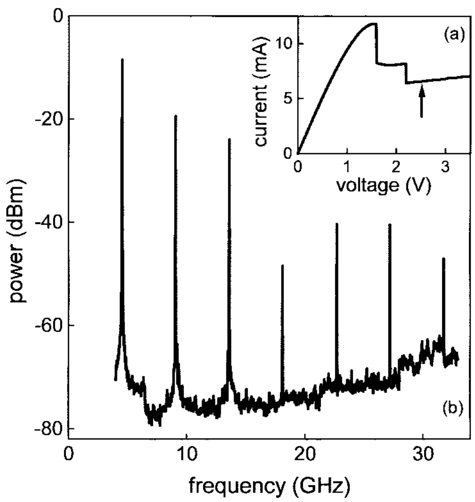

Fig. 2. (a) I–V characteristic of the superlattice and (b) microwave spectrum generated by the free superlattice oscillator.

was about 130 μW. The power decreased by a factor of four for each following ultraharmonic.

The free oscillator generated radiation at ν_0 in a band of a halfwidth of about 0.5 MHz (Fig. 3). Applying a field at the driving frequency ν_1 resulted in the suppression of the free oscillation and, in turn, to the appearance of a locked oscillation, with generation of microwave radiation at ν_1 (Fig. 3) within a bandwidth (halfwidth $\leq$ 10 Hz) that was (within our resolution) almost equal to that of the driving field. The noise level of the locked oscillator was very small (at a distance 20 Hz away from ν_1 the microwave power was 40 dB lower than in the peak); sidebands (50 Hz away from ν_1) were due to a cross talk from the power supply of the external microwave source. The power of the locked oscillator was the same as the power of the free oscillator. The difference in the peaks of the curves of Fig. 3 is a consequence of different frequency windows (10 kHz and 10 Hz) chosen for the registration of the broad and the narrow line. The microwave radiation has been recorded with an attenuator (8 dB, Fig. 3) between microwave circuit and spectrum analyzer.

The frequency locking occurred if the power of the driving field exceeded a threshold power P_{th}, which increased [Fig. 4(a), points] almost quadratically with the frequency distance $|\nu_1 - \nu_0|$. The power of the driving field was much smaller than the power of the locked oscillator P, which was independent of ν_1 [Fig. 4(a), upper points]. In Fig. 4(b) we have plotted, in linear scales, the dependence of P_{th} on the locking range 2 $|\nu_1 - \nu_0|$. At a power of 10 μW of the external field, a locking range of nearly 50 MHz (1% of ν_0) was reached.

The locked oscillator emitted narrowband microwaves also at the ultraharmonics of the driving frequency, with a power that was the same as for the ultraharmonics of the free oscillator; for all ultraharmonics which we studied (up to the seventh, at 32 GHz) the linewidths were below 10 Hz.

IV. Discussion

Our result indicates that the external microwave field imposed boundary conditions to the domain formation, resulting

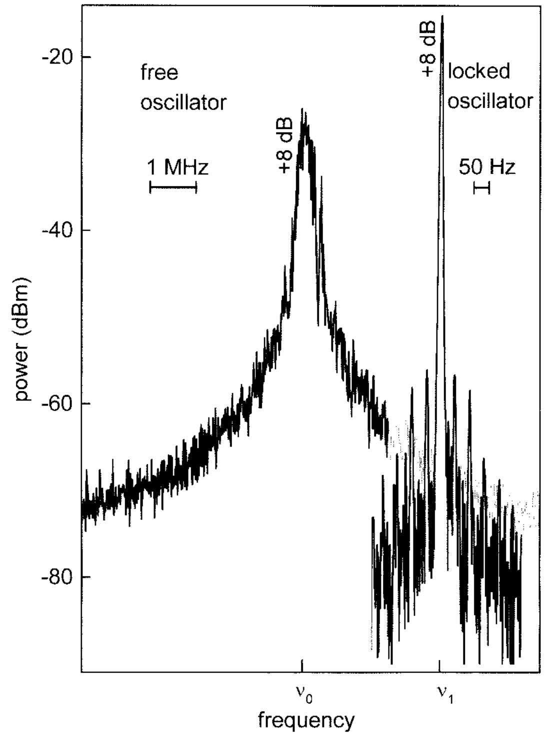

Fig. 3. Spectrum of the free superlattice oscillator with a line at the natural frequency ν_0 (near 4.6 GHz) drawn at a frequency scale of 1 MHz, and of the locked oscillator with a line at the driving frequency ν_1 about 3 MHz away from ν_0, now drawn at a frequency scale of 50 Hz.

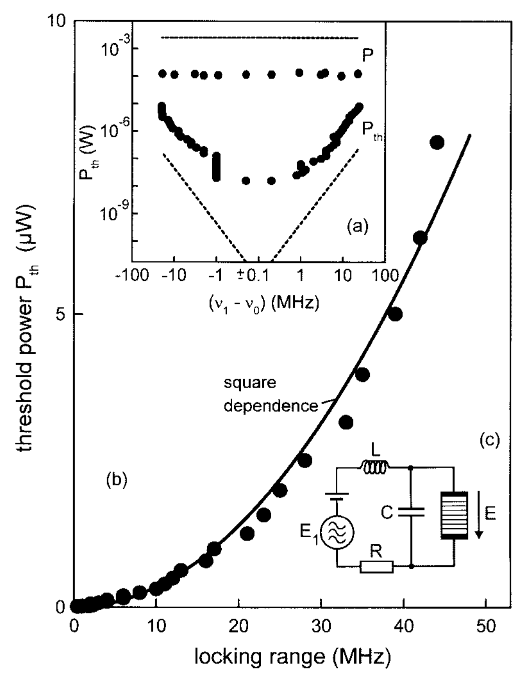

Fig. 4. (a) Threshold power for the locking and power of the locked oscillator, experiment (points), and theory for a lossless circuit (dashed lines); (b) threshold power and locking range; and (c) simplified circuit model of the locked oscillator.

in the locking of the current oscillation to the external field and in the line narrowing; we suggest that temperature fluctuations in the superlattice and charge density fluctuations at the superlattice boundaries (toward highly doped graded layers) were responsible for a fluctuation of the natural frequency (and its harmonics) of the free oscillator.

The frequency of the free oscillation was tunable by about 10% (400 MHz) by changing the bias voltage. Correspondingly, it was possible—by tuning the driving frequency together with the bias voltage—to perform frequency locking over the same frequency range. Taking into account that besides a narrow harmonic narrow ultraharmonics are also generated, the locked superlattice oscillator represents a tunable microwave source covering a wide frequency range.

The locking behavior we observed is typical for a self-sustained oscillation submitted to an external force. For a first analysis of our results we describe, for simplicity, the oscillator by a circuit [Fig. 4(c)] consisting of the SLED in parallel with an LCR circuit (L, inductance; C, capacitance; R, resistance), which contains the dc and the external high-frequency source. In the steady state of the locked oscillator, the complex amplitude E of the high-frequency voltage across the superlattice is given by $E = -ZI + \lambda E_1$, where Z is the impedance of the LCR circuit, $I = ES$ is the complex amplitude of the high-frequency current through the superlattice, S is the large-signal conductance of the superlattice, E_1 the complex amplitude of the voltage of the external field, and λ is a coupling factor given by the ratio E/E_1 at zero current through the superlattice, which is for $R \ll 2\pi\nu_0 L$ and for a frequency ν_1 in the vicinity of ν_0, given by $\lambda^{-1} = -2(\nu_1 - \nu_0)/\nu_0 + 2\pi i \nu_1 CR$. We have, for $E_1 = 0$, a self-sustained oscillation, where $CR + LS(E) = 0$. It follows for the threshold power P_{th}, necessary for the locking

$$P_{th}/P = 4(\nu_1 - \nu_0)^2/\nu_0^2 \qquad (1)$$

where P is the microwave power generated by the free oscillator; we assumed, as suggested by the experiment, that for the locked oscillator E was independent of E_1 and ν_1. According to (1) the threshold power is proportional to the square of the frequency distance between ν_1 and ν_0, as observed in the experiment. Taking into account a loss factor of ten for the transfer of the external radiation to the superlattice and another factor of ten for the transfer of the radiation from the superlattice to the frequency analyzer, we obtain the theoretical curves (with the loss eliminated) shown as dashed lines in Fig. 4(a); at $|\nu_1 - \nu_0| = 10$ MHz, the theoretical ratio P_{th}/P is about 10^{-4}, indicating that the amplitude of the driving voltage across the superlattice was by a factor of the order of 100 smaller than the amplitude E of the total high-frequency voltage across the superlattice. By reducing the loss, which was caused mainly by the epoxy substrate and nonperfect matching of the electronic parts of the network, it should be possible to improve the locked superlattice oscillator toward generation of higher power at lower threshold power—in our present device toward the dashed lines in Fig. 4(a).

We note that (1) is also obtained for a locked van der Pol oscillator [3]; however, while the large-signal high-frequency conductance is given for a van der Pol oscillator by a tunnel diode like I–V characteristic, it is for the superlattice oscillator determined by an Esaki–Tsu I–V characteristic [4] modified because of domain formation. Equation (1) is characteristic, as has been found in an earlier study [5], for an active device coupled to an LCR circuit.

It has been shown that a Gunn oscillator can be frequency locked [6]. An oscillator emitting high-frequency waves at a frequency of 30 GHz (power 10 mW) was locked by an external field (power 1 mW); a locking range of 2 MHz (about 10^{-4} of the free-oscillation frequency) was reported. The frequency locking, on the basis of the nonlinear I–V characteristic of the Gunn oscillator, has been analyzed [6] by use of van der Pol's oscillator. The intraminiband relaxation time ($\sim 10^{-13}$ s) of a GaAs/AlAs superlattice, which determines an upper frequency limit for the SLED, is an order of magnitude smaller than the intervalley relaxation time, which determines the frequency limit of Gunn elements. Therefore, a locked superlattice oscillator may be suitable for generation of tunable monochromatic radiation at much higher frequencies than a locked Gunn oscillator.

We expect that locking, as demonstrated for our 5-GHz oscillator, should also be achievable for a superlattice oscillator which has a much higher natural frequency of the self-sustained oscillation. A higher natural frequency is obtained for a superlattice with a miniband of larger width. Recently, a natural frequency of 65 GHz has been achieved [7], and higher harmonics of a natural frequency of 36 GHz up to 180 GHz were observed [2].

In conclusion, we have demonstrated frequency locking of a superlattice oscillator by a weak narrowband external microwave field. We expect to obtain narrowband microwave radiation above 100 GHz by locking superlattice oscillators which operate with wide-miniband superlattices.

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