A Third Order Harmonic Oscillator Based on Coupled Resonant Tunneling Diode Pair Oscillators

Koichi MAEZAWA(†), Senior Member, Takashi OHE†, Student Member, Koji KASAHARA†, and Masayuki MORI†, Nonmembers

SUMMARY A third order harmonic oscillator has been proposed based on the resonant tunneling diode pair oscillators. This oscillator has significant advantages, good stability of the oscillation frequency against the load impedance change together with capability to output higher frequencies. Proper circuit operation has been demonstrated using circuit simulations. It has been also shown that the output frequency is stable against the load impedance change.

key words: resonant tunneling diode, oscillator, coupled oscillators, THz sources

1. Introduction

A resonant tunneling diode (RTD) is an ultrahigh frequency device showing a negative differential resistance (NDR). This NDR works as a basis for oscillators, and they are promising for future THz signal sources. The RTD oscillators were intensively studied from 1980s to early 1990s [1]–[4]. Ultrahigh frequency oscillations up to 712 GHz were demonstrated in 1991 [5]. However, research activities on this field declined after those days due to the lack of real applications. Recently, increasing attention to THz wave technology revived the interests in RTD oscillators [6]. A record high-frequency oscillation of 831 GHz has been reported most recently [7], and also the THz signal generation based on harmonics has been also reported [8].

The RTD oscillators, however, still have some difficult problems for practical applications. The first is a bias instability due to the NDR itself, which exists from dc to THz frequency range [9]. This often causes a low frequency spurious oscillation. The second is a frequency instability caused by the variation of the load impedance. RTDs have only two terminals, so that the isolation of the core oscillation circuit from the output load is difficult. Though an isolator or circulator can be used for this purpose, conventional isolators/circulators are difficult to apply in the frequency range we are interested in (higher than 100 GHz). Optical isolators are also difficult to apply this frequency range.

To overcome the first problem, we proposed and demonstrated the RTD pair oscillators consisting of series connected RTDs [10]–[12]. In this paper, we propose a harmonic oscillator based on the coupled RTD pair oscillators to solve the second problem.

2. RTD Pair Oscillators

Figure 1 shows the basic circuit configuration of the RTD-pair oscillator [10]. This oscillator consists of two RTDs connected serially and a resonator connected to the node between the two RTDs. The serially-connected RTDs are biased by voltages with the same absolute value with the opposite sign. The most significant advantage of this is that it separates the oscillation node from the bias nodes. This permits us to connect large capacitors (CS) to the bias nodes, which stabilize these nodes, while they have no effect on the high-frequency oscillation. This is in contrast with the conventional RTD oscillators.

We first fabricated the circuits based on the RTDs on InP substrates and demonstrated basic operations [11]. Next, we fabricated the circuits on the AlN ceramic substrates employing novel heterogeneous integration technology [12]. This integration enabled us to mount large chip capacitors close to the core circuit, which further stabilized the circuits.

3. Coupled RTD Pair Oscillators

As described above, there are two problems when applying RTD oscillators to real applications. The first problem, the bias instability, can be solved by the RTD pair configuration. To solve second problem, sensitivity of the oscillation...
frequency to the load impedance, we have investigated to employ harmonic oscillator concept. Push-push type harmonic oscillators, employing second order harmonic, have been studied intensively [13]–[16]. This is because they have good phase noise properties as well as they can easily generate higher frequency signals. This type of oscillators is also expected to be robust against the load impedance variation. This is because the output terminal is regarded as grounded for the fundamental frequency signal, which implies that the fundamental frequency is not influenced by the load impedance change. Of course, the fundamental frequency can be changed through the harmonic signals. It should be small.

At first, we tried to employ the push-push type harmonic oscillator concept with the RTD pair oscillators. However, it was found that the second order harmonic signal is much weaker than that of the third one. This is shown in Fig. 2, where the oscillation spectrum of the RTD pair oscillator obtained by simulation was shown. This is due to the circuit symmetry. Then, we decided to use third order harmonic signal.

Figure 3 shows the basic circuit configuration of the third order harmonic oscillator based on the coupled RTD pair oscillators. This oscillator consists of three RTD pair oscillators connected to each other by transmission lines, which will be called “a common resonator” hereafter. The RTD pair oscillators are also connected together by transmission lines with star-like geometry, which will be called “a power combiner” hereafter, and the output terminal is connected to this node. This type of coupled oscillators is known to oscillate in three-phase mode under a certain condition [17], [18]. In most simple case, when the each branch of the common resonator has a length of 1/3 of the fundamental wavelength, the adjacent oscillator tends to delay by 120-degrees. This leads to three-phase mode oscillation. Nearly pure third order harmonic signal can be obtained from the output terminal, because the fundamental and second harmonic signals are canceled when it oscillates in a three phase mode. In an ideal case, the output of i-th oscillator, \( V_i \) \((i = 0, 1, 2)\) can be expressed as,

\[
V_i = V_{0i} e^{j(\omega_0 t - \frac{2\pi}{3}i)} + V_{20i} e^{j(2\omega_0 t - \frac{4\pi}{3}i)} + V_{30i} e^{j(3\omega_0 t - \frac{6\pi}{3}i)} + \cdots .
\]  

(1)

Then, the output of the overall circuit, \( V \), is

\[
V = V_0 + V_1 + V_2
\]

\[
= V_3 e^{j(\omega_0 t)} + \cdots .
\]  

(2)

(3)

Here, the fundamental and second order harmonics can be completely cancelled out.

We tested the above circuit using circuit simulation. The RTD was modeled by a parallel circuit of a voltage-controlled current source and a capacitor. The model equations and the parameters used for RTDs were the same as those described in the previous paper [10]. The individual oscillator consists of two RTDs with an emitter area of 10 \( \mu \)m\(^2\) and a resonator (transmission line having delay time of 2.5 ps). The peak current density of the RTD was \( 10^5 A/cm^2 \) and the capacitance was 2 fF/\( \mu \)m\(^2\). The circuit parameters for the individual oscillator is designed so as to oscillate at around 100 GHz. The strict oscillation frequency is expressed by the anti-resonance frequency of the parallel circuit consisting of a shorted transmission line and an RTD capacitance. It is somewhat smaller than the inverse of 4\times delay time of the transmission line. The details have been reported in [11].

Figure 4 shows an example of the oscillating waveform of the three RTD pair oscillators together with the output signal. The length of the common resonator was set to be 1/3 of the fundamental wavelength. The output was terminated with 50-Ohm pure resistive load. Three-phase mode oscillation is clearly demonstrated as seen in the figure. Moreover,
of phase, are often observed. Third order harmonic signal can be output even in this case, however, the output power decreases considerably. We simulated the circuit with various lengths of the common resonators to clarify this phenomenon. The results are shown in Fig. 5. This figure shows the dc to RF conversion efficiency together with the output frequency as a function of the delay time of the common resonators. The power combiner delay time was fixed to be 3.2 ps. The delay time was used instead of the electrical length, since the fundamental frequency also changes with the length of the common resonator. The delay time range for proper oscillation mode is shown in the figure. The range is sufficiently wide, 2 ps, which approximately corresponds to 1/6 of the fundamental wavelength.

Figure 6 shows the proper three-phase operating range of the power combiner delay time. A delay time of the common resonator was fixed to be 4.2 ps. As shown in the figure, the proper operation can be obtained in a wide range of the power combiner delay time. These results indicate that the third harmonic RTD pair oscillator is robust against the parameter scatterings.

Practically, non-uniformities in circuit parameters of the individual oscillators cause some leakages of the fundamental and second order harmonics to the output. In this case, a high pass filter (HPF) should be added to the output line for reducing such leakages. We investigated the effect of non-uniformities by simulation assuming dispersion in RTD areas. We confirmed that the leakage power of the fundamental signal is so small, less than 10% for the RTD areas having standard deviation of 0.5 \( \mu m^2 \) with \( 10 \mu m^2 \) average. This fact together with the larger frequency ratio by using third-order harmonic indicates that the requirement for the HPF is not severe. Note that the second order harmonic power is much smaller than the fundamental one.

4. Stability of the Output Frequency

Finally, we tested the sensitivity of the output frequency to
the variation of the load impedance. Figures 7, 8, and 9 show the simulation results of the output frequency as a function of the load impedance. The output frequencies of the single RTD pair oscillators are also shown in the figure for reference. Figure 7 shows the output frequency as a function of the load resistance. Even if the load impedance is purely resistive, the output frequency of the single oscillator changes at low resistance region. On the other hand, the output frequency of the coupled third order harmonic oscillator is stable against resistance change.

Figures 8 and 9 show the frequencies as a function of the inductance inserted serially to the 50Ω load, and as a function of the capacitance inserted parallelly to the 50Ω load, respectively. These dependences correspond to more real situations, where parasitic capacitance or parasitic inductance exists with the purely resistive load. As shown in the figures, the output frequencies for the single RTD pair oscillator change significantly even when very small capacitance of a few tens of a fF or very small inductance of a few tens of a pH exists at the load. On the other hand, the output frequency of the third order harmonic oscillator is almost independent of the load impedance. This demonstrates the robustness of the coupled third harmonic oscillators against the load impedance change.

5. Conclusion

We have proposed a harmonic oscillator based on the coupled RTD pair oscillators. We employ the third order harmonic instead of the second order harmonic because the third order harmonic is much stronger than the second one. Three phase operation has been demonstrated by circuit simulation. It has been also shown that the parameter ranges for the proper three phase operation are relatively wide. Finally, we demonstrated stability of the operation frequency against the variation of the load impedance. These results together with the ease of obtaining higher frequency demonstrate the promises of the proposed oscillator.

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References


**Koichi Maezawa** was born in Tokyo, Japan, in 1959. He received a B.E. degree in Applied Physics, an M.S. degree in Physics, and the Ph.D. in Applied Physics from Waseda University, Tokyo, Japan, in 1982, 1984, and 1993, respectively. He was engaged in the research and development of heterostructure FETs and quantum effect devices at NTT from 1984 to 1997 and at Nagoya University from 1997 to 2006. He is currently a professor at the Graduate School of Science and Engineering, University of Toyama. His current interests include heterostructure FETs, resonant tunneling devices, MBE growth of quantum structures, and applications of quantum functional devices to new architectures for computation. Dr. Maezawa is a member of the Japan Society of Applied Physics, the Physical Society of Japan, and a senior member of the IEEE.

**Takashi Ohe** was born in Gifu, Japan, in 1984. He received the B.E. and M.E. degrees in Electric and Electronic Engineering from University of Toyama, Toyama, Japan, in 2007 and 2009, respectively. He is now working on automotive semiconductor devices at Denso corporate, Aichi, Japan.

**Koji Kasahara** received the B.E. degree in Electronic Systems Engineering from Tokyo University of Science, Suwa, Japan, in 2008 and M.E. degree in Electric and Electronic Engineering from University of Toyama, Toyama, Japan, in 2010. He is now working for Dengensha Mfg. Co., Ltd. Kanagawa, Japan.

**Masayuki Mori** was born in 1969. He received his Ph.D. degree from Toyama University, Toyama, Japan in 1998. He is an assistant professor at University of Toyama, Toyama, Japan. His research interests are in the areas of crystal growth of semiconducting thin films and fabrication of electronic devices.