Possibility of High Order Harmonic Oscillators Based on Active Transmission Lines Loaded with Resonant Tunneling Diode Pairs

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1. Introduction

Recently, THz wave technology has been attracting a great deal of attention in a variety of application fields, which include wireless communications, medical, security, and biotechnology applications. Compact and coherent solid-state signal sources are the key components for these applications. A resonant tunneling diode (RTD) is one of the most promising devices for such applications. Negative differential resistance (NDR) of the RTDs is a basis for ultra-high frequency oscillators. A fundamental oscillation beyond 1 THz has been already reported [1], [2], and its NDR has been demonstrated to persist beyond 2 THz [3].

However, RTD oscillators have some difficult problems, bias instability, spurious oscillations [4], and frequency instability caused by the variation of load impedance. To overcome the first and second problems, we proposed and demonstrated RTD pair oscillators [5]–[7]. For the third problem, harmonic oscillators based on coupled oscillators should be a good solution. We have already proposed a 3-phase coupled RTD pair oscillator for this concept [8]. In this paper, we investigate another type of coupled RTD pair oscillators, which is based on an active transmission line periodically loaded with RTD pairs.

Nonlinear transmission lines (NLTLs) periodically loaded with RTDs can be regarded as active NLTLs amplifying the signal together with nonlinear signal processing [9]–[11]. The active TLs can also be a basis for high frequency oscillators [12]. Since the RTDs show strong nonlinear I-V curves, such oscillators should produce strong harmonic signals. In this paper, we will report on the properties of such oscillators based on circuit simulation with special attention to the behavior of harmonics. It is observed that high order harmonics can be efficiently generated with this type of oscillators. Harmonic oscillators based on this phenomenon are promising for high performance THz sources.

2. Oscillators Based on Active TLs

First, let us consider a uniform active transmission line, both ends of which are terminated as to reflect all signals \(|\Gamma| = 1\). Oscillation occurs at the frequency where a half wavelength or its integer-multiple equals to the TL length. If one end of the TL can pass a part of oscillation power, it can be a high frequency source, which is analogous to the laser.

Figure 1 shows a simple implementation of such circuit. We used RTD pairs instead of single RTDs, since they are more robust against bias instability and spurious oscillation problems [5]–[7]. The RTD pairs are biased by the voltages of the same absolute value with opposite signs. The current-voltage characteristics at the node between the two RTDs show a true negative resistance region at low voltages. The amplitude of this negative resistance can be controlled by adjusting bias voltage. From the symmetry of the RTD pair, even-order harmonics is much weaker than odd-order ones [8]. Then we designed the circuit having 3 RTD pairs, which is expected to be a most simple configuration advantageous for odd-order harmonic oscillators.

In this circuit, one end of the TL is grounded via a small resistance. This permits a part of oscillation power to transmit to the load. Though this resistor-based termination is not good from the view point of efficiency, we use here for simplicity. As described later, this resistor can be replaced by a high pass filter for efficiency when we apply this circuit for harmonic oscillators.

Fig. 1 The configuration of the oscillator circuit based on active TLs.

This line works as an oscillator, if both ends of the TL are grounded, the oscillation occurs when a half wavelength or its integer-multiples correspond to the length of the TL.
3. Results and Discussion

3.1 Simulation Model

We carried out circuit simulations to clarify the harmonic signal behavior of the above circuit using Agilent ADS. A simple RTD model consisting of a voltage-controlled current source and a capacitor connected in parallel together with a series resistance was used in the simulation. The model equations and the parameters used for RTD current source were the same as those described in the previous paper [5]. The peak current density, the capacitance, and the series resistance of the RTD were assumed to be $10^5 \text{ A/cm}^2$, $2\text{ fF/\mu m}^2$, and $10\Omega \cdot \text{\mu m}^2$, respectively. The RTD area was $10\text{ \mu m}^2$.

3.2 Basic Properties

Figure 2 shows an example of the transient simulation results. Here, the TL length A and B are designed to have same length corresponding to the delay time of 6.25 ps, and the TL impedance is 100$\Omega$. As seen in the figure, internal nodes (n1, n2, n3) oscillate in a same phase, which indicates the fundamental oscillation has a wavelength that is twice the total TL length. It is also seen that the output waveform includes higher frequency components.

Figure 3 shows the result of Fourier transformation of the output waveform. Besides the fundamental frequency of 18.16 GHz, there is a strong peak at 163.4 GHz. This peak corresponds to the 9th order harmonic. On the other hand, the 3rd, 5th, and 7th order harmonics are very weak. This is a very interesting result. If such a high order harmonic is used for harmonic oscillators, various advantages are expected [13] especially in THz region. First, it relaxes the stringent requirement for circuit and device parameters for high frequency fundamental oscillators. Second, the phase noise should be improved due to mutual coupling behavior of devices, and also, due to higher $Q$-value expected for lower frequency resonators. Moreover, the frequency instability due to the load impedance variation is reduced because the fundamental frequency can be confined in the resonator as shown in Sect. 3.4. This is a significant advantage for the RTD oscillators because RTDs cannot isolate input/output terminals.

Next, we investigated the conditions to obtain such high order harmonics. It is found that the power of the 9th order harmonic strongly depends on the TL length ratio, $r_{AB} (= \text{length of TL A/length of TL B})$. This is shown in Fig. 4. As shown in the figure, 9th order harmonic is stronger around $r_{AB} = 1$. Moreover, we often observed change of fundamental oscillation mode from $\lambda/2 = (\text{Total length of TLs})$ to $3\lambda/2 = (\text{Total length of TLs})$ at $r_{AB} \geq 2$, depending on the initial conditions.

In addition, we found that the TL impedance has a
strong impact on the spectrum. Figure 5 shows the frequency of the strongest high order harmonic together with the fundamental frequency as a function of TL impedance. The order of strongest harmonic is also shown in the figure. With increasing the TL impedance, the fundamental oscillation frequency decreases because the effect of RTD capacitance becomes larger. The order of strongest harmonic changes from 7 to 11 with the TL impedance increases.

One of the most important points is that the frequency of the strongest harmonic signal remains in a range from 150 GHz to 200 GHz, even when the order of the harmonic changes. In Addition, it is observed that the power of the harmonic signal peaked at around 170 GHz, and decreases rapidly when approaching to 150 and 200 GHz. This implies that there is a passband and this phenomenon is caused by frequency locking. Figure 6 shows the transmission coefficient of the (active) TL in the oscillator, when the RTDs are replaced by pure capacitors. In principle, this circuit can be regarded as a low pass filter, as shown in the frequency range lower than 70 GHz. At higher frequencies, however, there are some resonances due to the discreteness of the circuit. In fact, there is a passband around 170 GHz, which agrees well with the strongest harmonic frequency. Consequently, high order harmonic can be generated when integer-multiple of the fundamental frequency matches this passband. The TL-ratio dependence can also be addressed to this phenomenon. It should be noted that we can design such high frequency passband independent of the fundamental frequency. This should be an important advantage to design harmonic oscillators.

One exception of this mechanism is the 3rd order harmonic (around 60 GHz), which is very weak though it is in the low frequency pass band. We think this can probably be explained by the difference in the mode of oscillation. The RTD pairs oscillate in a same phase for the harmonics showing strong intensity (7th, 9th, 11th). This is the same as the fundamental oscillation. On the other hand, the oscillation of the center and side RTD pairs are inverted (180 degree phase difference) for the 3rd order harmonic. This can reduce the gain for the 3rd harmonic wave due to the nonlinear I-V characteristics of the RTD pairs. Further studies are needed to clarify this phenomenon.

3.3 Stability

We have tested the stability of the circuit against the variation of circuit parameters. Figure 7 shows the harmonic power against the RTD area variations. We varied the RTD area randomly, and plotted each harmonic power as a function of the standard deviation of RTD area. The average RTD area and the other parameters are the same as used for Fig. 3. It shows that the power of 9th order harmonic is always larger than the 3rd, 5th and 7th order harmonic in spite of RTD area variations.

3.4 Circuit Design for Practical Use

The oscillator circuit shown in Fig. 1 is not practical, because the most of the signal current flows into the small output resistor and the output power is very small. If we replace this resistor by a high pass filter (HPF), the oscillator can output harmonic signal efficiently, while it confines
the fundamental oscillation. Here, we tested the circuit having 2-stage LC π-type HPF. The output spectrum is shown in Fig. 8. The π-type HPF is used because it works as a short grounded terminal for low frequencies. As shown in the figure, 9th order harmonic signal is efficiently output while the fundamental frequency is almost diminished. It is noted that the requirement for HPF relaxes considerably because we can use the high order harmonic.

4. Conclusion

We have studied the oscillators based on an active transmission line periodically loaded with RTD pairs. Generation of very high order harmonic was observed for these circuits. The mechanism of this phenomenon was discussed, and concluded that it is caused by the frequency locking in the high frequency passband. Stability of the circuit and the design for efficient output were also discussed. Consequently, the harmonic oscillators based on this phenomenon are promising for high performance THz sources.

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