Injection Phase-locking of a High-power Transit-time Oscillator

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Abstract— The enhancement of microwave power density at a certain extent is one of the most significant problems in the development and application of the high power microwave (HPM) sources. Limited by the power capacity and radio frequency (RF) breakdown issues, a single HPM device can hardly achieve high output power. The spatial power combining among several HPM sources is a feasible method. A transit-time oscillator (TTO) with advantages of stability, simple structure, and high beam-wave interaction efficiency, is one candidate for spatial power combining. To lock the phases of the output microwaves of different TTOs, a Ku-band coaxial transit-time oscillator with an injection structure is presented. Between the independent input cavity and the trinal-cavity buncher, a reflector with reflection efficiency of 99.9% is introduced to prevent the leakage power propagating to the input cavity. The RF signal is injected into the input cavity through a coaxial waveguide along the guiding magnet, which avoids separating the magnet coils, and suppresses the asymmetric modes excited in the device. Particle-in-cell (PIC) simulation results indicate that when the injection power ratio ρ ($\rho^2 = P_{in}/P_{out}$, where P_{in} is the injection power, and P_{out} is the output power of the oscillator) is large ($\rho \sim 0.1$), the phase-locking is achieved for a frequency difference of 67 MHz. When the injection power ratio is small ($\rho \sim 0.01$), the phase of the device with the same frequency can be locked ($\Delta f \sim 2$ MHz). It has also been found that the injected signal of high power results in higher output power and earlier saturation than that of a TTO without the injection structure. Moreover, a wider locking bandwidth is expected by the results than that obtained by the Adler's condition.

1. INTRODUCTION

Enhancing the operation frequency and the output power of high power microwave (HPM) sources is the developing trend of HPM technologies [1]. At present, a gigawatt-level output power of microwave sources has been achieved at the relative low frequency bands, such as P-band, L-band, C-band and X-band [2]. However, at the higher frequency band, like Ku-band which is widely used in the broadcasting and communications, the microwave sources mostly can only obtain a megawatt-level output power. This is mainly limited by the decreasing power handling capacity of smaller structure dimensions. An alternative approach is to combine the power of several HPM sources spatially. Many investigations have indicated that combining the power of several phase-locking HPM oscillators is a logical and promising approach for enhancing the output power [3–5]. In order to combine the output power of multiple HPM sources in an antenna array efficiently, the sources must be phase-locked at the same frequency.

The microwave source is a significant part of the combining system. The transit-time oscillator (TTO) has been intensely investigated recently due to its merits such as simple structure, pure frequency and high power [6]. In addition, the coaxial TTO is low impedance, high power capacity and needs a low guiding magnetic field, which make it an ideal HPM source for power combining. Due to above virtues, a coaxial TTO with an injected signal to lock its phase is proposed in this paper. An input cavity and a resonant reflector are designed to increase the injection efficiency and suppress the TEM mode leakage to the input cavity, which will be demonstrated in Section 2. Section 3 show the phase-locking results under different conditions, and the locking bandwidth for different injection power ratios will be presented. A short summary is given in Section 4.

2. STRUCTURE MODEL

The schematic structure of the coaxial TTO with an injected signal is shown in Figure 1, mainly consisting of eight parts: a cathode, an input cavity, a resonant reflector, a modulation trinal-cavity, a dual-cavity extractor, a beam collector, a sloping wedge, a coaxial waveguide and a coaxial injection structure. An independent input cavity with injection efficiency of 98% is designed. The injected signal propagates through a coaxial waveguide which avoids separating the magnet coils, and then reaches the input cavity through a sloping wedge which connects the waveguide and the input cavity. A resonant reflector is located between the input cavity and the modulation trinal-cavity to suppress the communications between them, namely, to reduce the influence of the leakage power from the modulation trinal-cavity on the normal operation of the input cavity. By optimizing

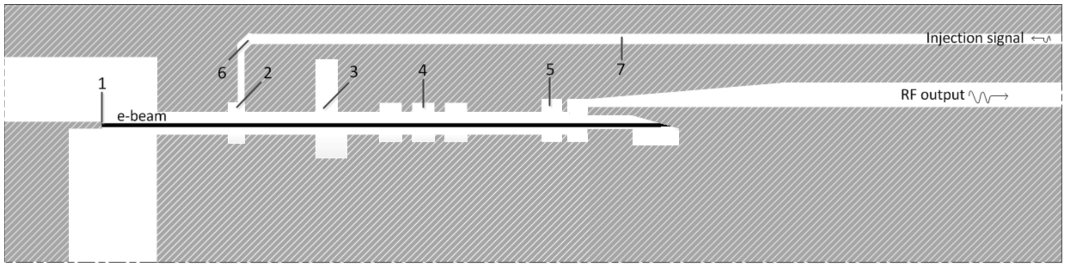

Figure 1: Schematic diagram of the coaxial TTO. 1 cathode, 2 input cavity, 3 resonant reflector, 4 modulation trinal-cavity, 5 dual-cavity extractor, 6 sloping wedge, 7 coaxial waveguide.

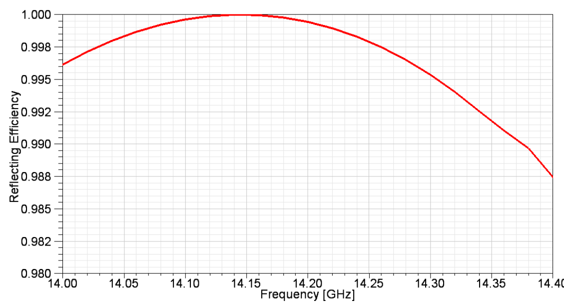

Figure 2: The reflection efficiency of TEM mode of the resonant reflector.

the distribution of the electric field and distances between the three types of cavities, the reflection efficiency of the TEM mode is made above 99.8% in the frequency range of 14.04–14.25 GHz, which is shown in Figure 2. The remainder of the structure has the similar function with that of the coaxial TTO proposed in Ref. [7].

3. SIMULATION RESULTS

A PIC code KARAT [8] has been used to demonstrate the phase-locking process of TTO.

To observe the phase control process of the output signal, the injected signal is defined as the reference signal. The phase-locking characteristics of the output signal can be confirmed by comparing the relative phase of the output signal and the reference signal.

Assuming the frequency of the reference signal is f_r, the initial phase of the reference signal is φ_0, which are equal to that of the injected signal. f and φ are the frequency and the initial phase of the output signal, respectively. Then the relative phase can be given by:

$$\Delta\varphi = 2\pi\left(f - f_r\right)t + \left(\varphi - \varphi_0\right) \tag{1}$$

From Eq. (1), one can ascertain that the relative phase keeps at $\varphi - \varphi_0$ when $f = f_r$.

The operation frequency and output power of the proposed structure are 14.164 GHz and 900 MW, respectively when there is no injected signal. The relative phases for different injection power and different initial phase of the injected signal are illustrated in Figure 3 when the injection frequency is identical with the free-running frequency ($f_r = 14.164$ GHz).

As shown in Figure 3(a), when the injection power is low ($\sim$10 kW, $\rho\sim$0.003), the relative phases between the injected signal and the output signal levels off with a fluctuation of 6° with different initial phases of the injected signal (0°, 45°, 90°), which means the frequencies of the output signals is almost consistent with the free-running frequency. And the phase-locking is achieved.

Figures 3(b) and 3(c) illustrate that when the injection power increases ($\sim$100 kW, $\rho\sim$0.01: $\sim$1 MW, $\rho\sim$0.03), both of the relative phases show an ascending trend, indicating that there should be a frequency excursion ($f > f_r$, due to Eq. (1)) between the frequency of the output signal and the injected signal. Figure 4 further confirms it. While injecting signals of 100 kW or 1 MW power, the average frequencies of the output signals are both higher than the free-running frequency of the TTO. The variety of the injection power results in the changes of the intrinsic field of the cavity in TTO, leading to a frequency drift [8]. An injection power of 10 kW is too low to obtain a visible frequency drift, therefore the average frequency of the output signal is approximately equal to the free-running frequency ($f - f_r \approx 0$), as shown in Figure 4. The relative phases with different initial phase of the injected signal are nearly identical in Figures 3(b) and 3(c), which means the initial phase of output signal can be still controlled. In this case, if the frequency of the injected signal is equal to the virtual operation frequency of the TTO, phase-locking can be achieved.

When the injection power reaches 10 MW ($\rho \sim 0.1$), the relative phase is constant after about 27 ns as shown in Figure 3(d). The average frequency of the output signal is consistent with the injection frequency (Figure 4), which means that not only the initial phase but also the frequency of the output signal can be locked under a condition of a 10 MW injection power. And the relative phases for different injection frequencies are illustrated in Figure 5, indicating that in the frequency range of 14.125–14.192 GHz, each relative phase difference fluctuates less than 8°.

With an injection frequency of 14.164 GHz and an injection power of 10 MW, the relative phase is investigated when the injected signal is stopped after operating for 60 nanoseconds as presented in Figure 6. After the injected signal is stopped, both the phase and the frequency fail being locked. It can be concluded that the phase-locking process needs a consecutive injected signal.

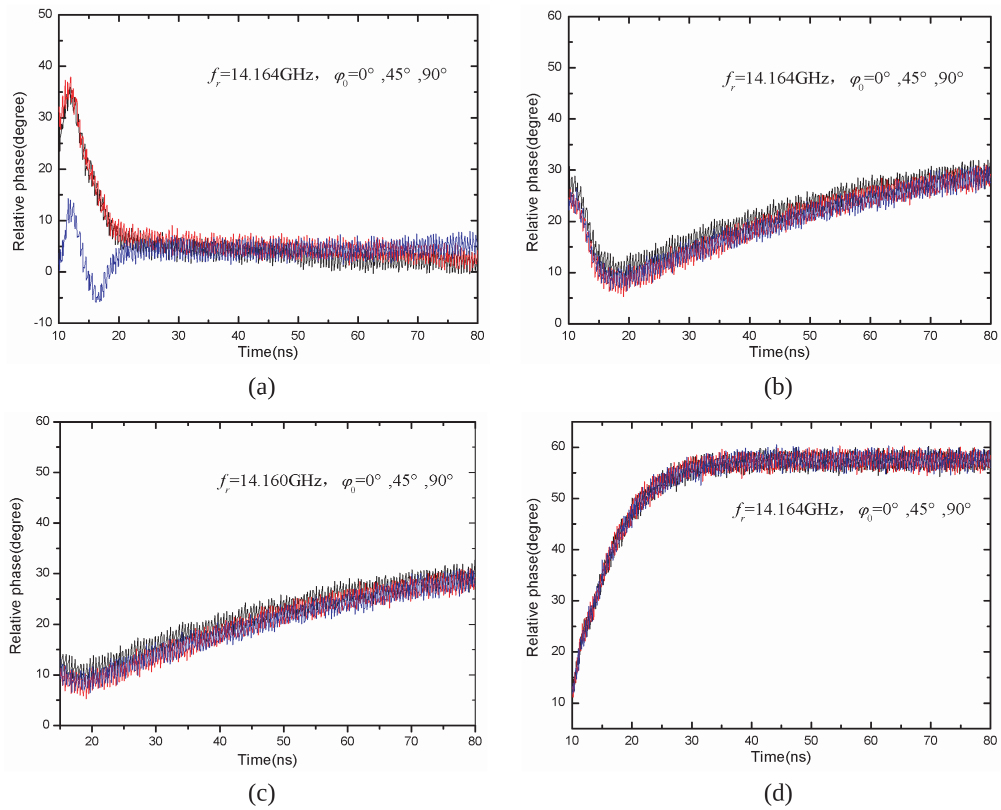

Figure 3: Relative phases for different injection power and different initial phases of the injection signal. (a) 10 kW. (b) 100 kW. (c) 1 MW. (d) 10 MW.

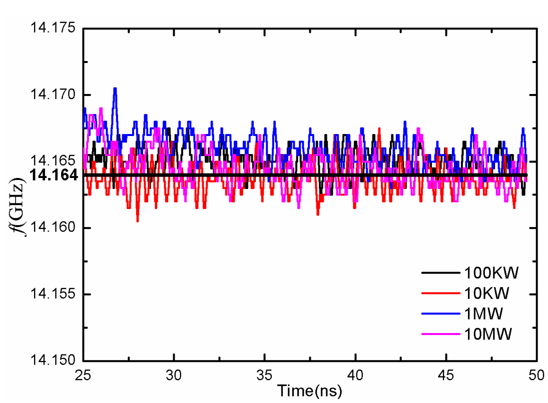

Figure 4: Frequency vs simulation time for different injection power.

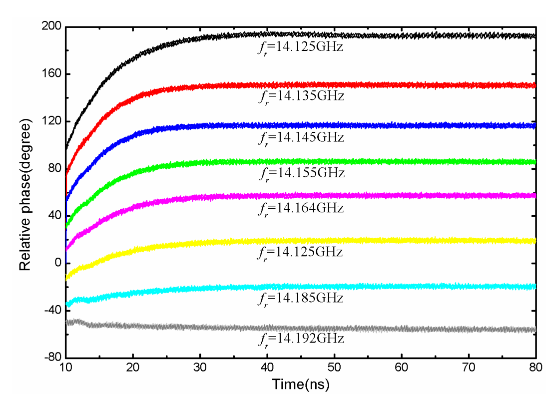

Figure 5: Relative phase for different injection frequency. Here, $\varphi_0 = 0°$.

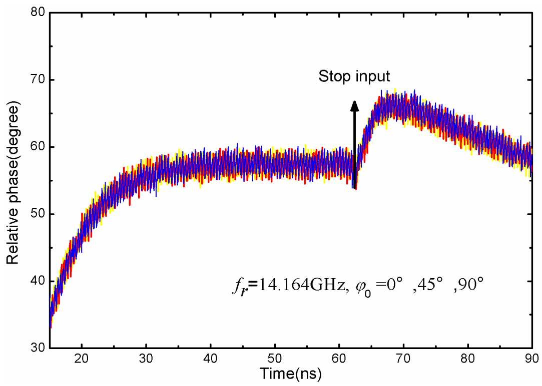

Figure 6: The relative phase under condition of an injected signal stopped after 60 ns.

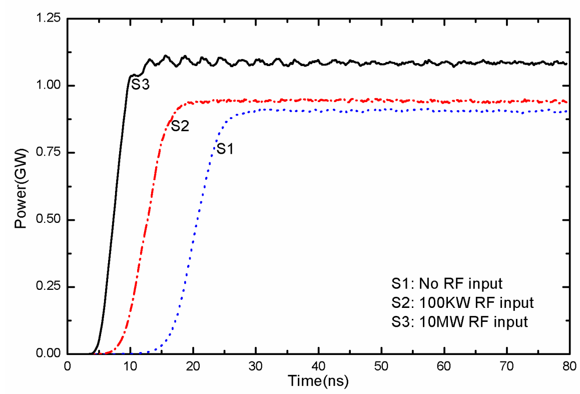

Figure 7: The output power for different injection power.

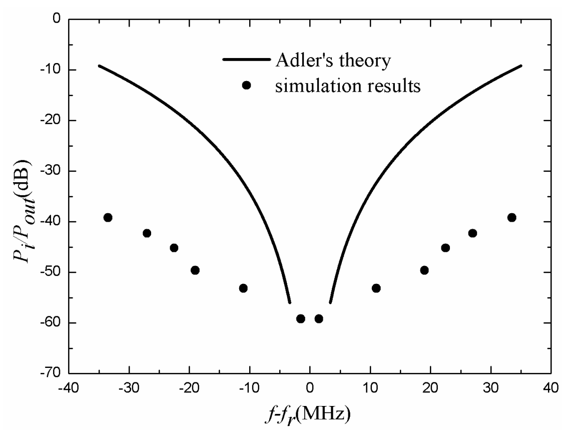

Figure 8: Comparison of the locking bandwidth for different injection power ratios. Solid dots: the condition proposed in this communication, solid line: the conventional phase locking theory. Here, $Q = 1600$, $f_r = 14.164$ GHz.

It can be seen from Figure 7 that the increasing injection power can enhance the output power and accelerate the saturation, which suggests the feasibility that the injected signal can greatly improve the output capacity of the microwave source.

The phase-locking bandwidth as a function of the power ratio between the injection power and output power is shown in Figure 8. It can be seen that the injection power needed to achieve phase-locking is much lower than that predicted by Adler's theory [9] for the same phase-locking bandwidth. When the frequency difference between the injected signal and the output signal is 19 MHz, an injection power of 3 MW is sufficient to lock the phase of a 1 GW output microwave.

4. CONCLUSION

A coaxial TTO with an injected signal is investigated in this article. In the device, an independent input cavity and a resonant reflector are designed before the modulating trinal-cavity to increase the injection efficiency and to decrease the leakage power respectively. The simulation results demonstrate that a high-power injected signal can lock the frequency and phase of the proposed device and improve the output capacity. When the frequency mismatch between the injected signal and the free-running coaxial TTO is ±33.5 MHz, an injection power of 10 MW can lock the phase of 1.1 GW microwave. Moreover, although a small injected signal can hardly lock the operation frequency of the device, the phase of output microwave can be controlled. Simulation results also show that the injection power needed to achieve phase-locking is much lower than that predicted by Adler's theory.

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