



Research Paper / Makale

RF Blocks for Biomedical Engineering

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Abstract: Radio Frequency (RF) power amplifier (PA), power oscillator (PO), mixer, and their test circuit simulation results were presented for biomedical engineering applications. The novel efficient Class-E type RF PA was designed, and a schematic circuit was simulated. RF circuit blocks were designed and implemented at the 130 nanometers (nm) standard CMOS RF technology. Schematic test circuit simulations were tested with antenna connection which includes two-wire bonding inductances and antenna inner resistance. According to the circuit simulation results, no extra mismatch tuning circuit was needed between PA, PO, and mixer output and antenna input stages. For demonstration purposes, 33 GHz extremely high frequency (EHF) band PA input voltage was applied at 300 mV peak-to-peak (pp) voltage level. Technology standard 1V RF n-channel Metal-Oxide-Silicon (MOS) transistor was used as a Class-E type active transistor switch. For PA circuit simulation, test results show that the proposed circuit runs better than traditional Class-E type RF PAs. 70% power amplifier efficiency (PAE) for -8.5 dBm power input at 33 GHz RF input frequency for 40 harmonics and 15 steps in the harmonic shoot balance mode was achieved. The whole circuit blocks were designed and implemented for biomedical engineering which was specifically requested for the glucose detection system.

Keywords: Class-E type RF Power Amplifier (PA), n-channel MOS (nMOS) RF MOSFET, biomedical engineering, glucose detection, power electronics, RF Power Oscillator (PO), indoor wireless telecommunication, biomedical engineering applications, mixer, millimeter wave (mmWave), extremely high frequency (EHF) band, low-noise amplifier (LNA), power supply.

Biyomedikal Mühendislik için Tasarlanmış RF Elektronik Devre Blokları

Öz: Biyomedikal mühendisliği uygulamaları için Radyo Frekansı (RF) güç amplifikatörü (PA), güç osilatörü (PO), karıştırıcı ve test devresi simülasyon sonuçları sunulmuştur. Yeni, verimli Sınıf-E tipi RF PA tasarlandı ve şematik devre simüle edildi. RF devre blokları 130 nanometre (nm) standart CMOS RF teknolojisinde tasarlanmış ve uygulanmıştır. Şematik test devresi simülasyonları, iki tel bağlama endüktansı ve anten iç direnci içeren anten bağlantısı ile test edilmiştir. Devre simülasyon sonuçlarına göre, PA, PO ve mikser çıkışı ve anten giriş aşamaları arasında ekstra uyumsuzluk ayar devresine ihtiyaç duyulmadı. Gösterim amacıyla, 33 GHz aşırı yüksek frekans (EHF) bandı PA giriş voltajı, 300 mV tepeden tepeye (pp) voltaj seviyesinde uygulanmıştır. Sınıf-E tipi aktif transistör anahtarı olarak teknoloji standardı 1V RF n-kanallı Metal Oksit-Silikon (MOS) transistörü kullanıldı. PA devre simülasyonu için test sonuçları, önerilen devrenin geleneksel E Sınıfı tipi RF PA'lardan daha iyi çalıştığını göstermektedir. 40 harmonik için 33 GHz RF giriş frekansında -8,5 dBm güç girişi için % 70 güç amplifikatörü verimliliği (PAE) ve harmonik atış dengesi modunda 15 adım elde edilmiştir. Tüm devre blokları, özellikle glikoz algılama sistemi için talep edilen biyomedikal mühendisliği için tasarlanmış ve uygulanmıştır.

Anahtar kelimeler: E sınıfı RF Güç Kuvvetlendiricisi (GK), n-kanallı MOS (nMOS) RF MOSFET, biyomedikal mühendisliği, glukoz sezme, güç elektroniği, RF Güç Osilatörü (GO), kablosuz haberleşme, biyomedikal mühendislik uygulamaları, mikser, milimetre dalga (mmDalga), çok yüksek frekans (EHF) band, düşük gürültülü kuvvetlendirici (LNA), güç kaynağı.

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1. Introduction

The novel Radio Frequency (RF) power oscillator (PO) circuit was designed, and simulation results were also presented. The PO circuit concept is extremely useful since it is using a single nMOS transistor as the switch element between input and output. It is also eliminating the usage of oscillator circuits for the transmitter side of RF circuits. Oscillator circuits have been usually implemented by using negative resistance harmonic cross-coupled LC-tank voltage-controlled oscillator (LCVCO) circuit structure with n-channel and p-channel standard CMOS technology transistors. Eliminating the traditionally used LCVCO circuit at the transmitter (Tx) side is important especially for indoor wireless telecommunication, and biomedical engineering systems, since the worth amount of power dissipation, is eliminated by using this method. For the implementation of PO, Class-E type RF PA was modified which was demonstrated in the PA circuit realization step. Its responsibilities are both generating oscillation signal and amplify its power to the antenna load. For this purpose, RF PO was also designed and implemented at the same 130 nm standard CMOS RF technology. Main supply voltage V_{dd} and bias voltage v_{bias1} were set to 600 mV. Totally 8.94-milliwatt (mW) average root-mean-square (RMS) power and 14.9 milliamperes (mA) RMS current were delivered from power sources at 35.6 GHz RF power oscillation frequency. This is the first study, which generates millimeter wave (mmWave) extremely high frequency (EHF) band (30-300 GHz) RF power oscillation with a single transistor. In the final step of whole circuit realization of glucose detection structure, a novel RF mixer circuit which runs in EHF band mmWave frequency is demonstrated. This mixer circuit is a completely new design and presented here first. Instead of using supply voltage to feed voltage and current of new concept single transistor mixer circuit, PO which has been introduced in the previous step was adopted. PO is supplying both supply voltage and current, it is also bringing baseband oscillation signal. By this method, both power supply and baseband oscillator signal were brought. This methodology is also eliminating the commonly used harmonic cross-coupled negative resistance feedback CMOS LCVCO circuit. On the other hand, instead of using complicated Gilbert Mixer architecture, the novel single transistor circuit design concept was used. The single transistor mixer circuit resembles the use of a low-noise amplifier (LNA) which has only one n-channel MOS transistor. According to the proposed mixer circuit design schematic, the second harmonic extraction of envelope signal was retrieved. 130 nm standard CMOS technology was also used. 35.6 GHz frequency PO signal and 34 GHz RF test signal was mixed, and a 3.12 GHz 2nd harmonic envelope was extracted. This work has not only one, instead of many novel design concepts. For the specifically requested purpose, detection of glucose molecules at the biomedical engineering field, radio frequency (RF) Class-E type RF power amplifier (PA), power oscillator (PO), and RF mixer circuits were designed and implemented for whole circuit structure implementation. A new feedback-loop class E-type PA circuit was chosen against other class PAs which are commonly used in the telecommunication field. Class-E type RF PA was chosen since Class-E type PAs achieve better energy transfer and low noise performance. Because it uses a fast active switch in the charge and discharge periods. The switch is usually chosen as an active transistor. It works based on the Normally Closed (NC) or Normally Open (NO) on/off switching principle. Since the switching transistor runs ON and OFF positions, it does not hold the high current and high voltage at the same time. This gives better power efficiency (PE) which eliminates much power consumption at the circuit. To achieve high PE, power consumption and dissipation should be lower which mostly depends on the active device transition times over amplifier load. Active switch element transistor should respond to desired running conditions. High current and high voltage should not exist at the same time. Generally accepted Class-E type PA circuit schematic and mathematical derivative formulas were given [1-3]. Parallel capacitance has been accepted as a reference circuit for a long time. Other variations around these reference circuits have been used by researchers. Zero voltage and zero current conditions for transistor switching were investigated [4]. It was shown that there is no zero voltage and zero current condition. Another variation was also tested which has a shunt inductor instead of using shunt capacitance [5]. Class-E type RF PAs have been used in wireless communication

systems. One of the circuit topologies which uses GaAs MESFET transistor with high PE was demonstrated with the power addition to load [6]. In the other work, class-E type PA circuits were used for communication systems [7]. 0.35- μm CMOS technology was used [7]. PA was also used as a power mixer; hence more than one transistor was used which reminds mixer circuit topology, combined with the mode-locking concept. This is good approach since it might eliminate the necessity of mixer circuit block in the RF integrated circuit (RFIC) receiver side design processes. The first power oscillator (PO) idea was introduced by J. Ebert and M. Kazimierczuk [8]. They theoretically formulated based on their first design concept single transistor Class-E type PA circuit schematic. The first feedback-loop circuit schematic topology has been illustrated in that work. To cut the input-output short circuit at the initial resonance time, they put extra inverse connected diode to the input of the circuit which increases the power dissipation of the circuit. POs are next-generation integrated oscillator + PA concept circuits for future wireless transmission, and RF-based biomedical engineering especially for imaging applications. Integrated PA and PO schematics were presented at the 0.13 μm CMOS technology [9]. Different injection mode PA design at modern technology was also introduced [10]. 5 GHz PA was designed for the wireless transmitter at the 0.18- μm CMOS technology [11]. In another work, class-E type RF PA was integrated into 0.18 μm standard CMOS technology. The power-added efficiency (PAE) was 34% in this work. Instead of using a single transistor, 2 switching n-channel MOS (nMOS) transistors were used to boost the performance of PA. It was succeeded 34.5% PAE at 0.18- μm CMOS technology [12]. When the capacitive feedback model was used, PAE level increased to 63% [13]. This work has shown that by using a feedback mechanism, PE is boosted. In another article, instead of using a single stage amplifier, two stages and a driver stage were used. It was simulated at 0.18- μm CMOS technology. Their PAE was better than single-stage PA, which was 48.3% [14]. Another two-stage structure was used to lower power dissipation; but on the other hand, their PAE was dropped to 29.9% [15]. In this work, a new feedback-loop PA test circuit was simulated. Instead of using a commonly accepted shunt capacitance model, a serially connected LC model circuit schematic was used which can be seen in Figure 2. It gave 70% PAE for -8.5 dBm power input at 33 GHz input frequency for 40 harmonics and 15 steps in the harmonic shoot balance mode.

2. Materials

2.1. Power Amplifier (PA) & Power Oscillator (PO) & Mixer Circuits

Indoor wireless telecommunication systems and biomedical engineering applications have become more popular last decade. For these research fields, making more compact circuits is very important, since power dissipation and electrical noises both are affecting system performances and requiring more battery life. Frequency band selection affinity has been inclined to extremely high frequency (EHF) band millimeter-wave (mmWave) RF signals which cover 30-300 GHz frequency bands for wireless telecommunication and biomedical engineering applications. For these application fields, simplified circuit architectures are preferable against complicated and high energy-consuming electric-electronic circuits. For example, it is easily preferred to use a simple transmitter (Tx) block instead of using complicated and high energy-consuming Tx block for the EHF band mmWave RF biomedical engineering application field. For this purpose, we designed and tested schematic circuit simulations of a single transistor Power Oscillator (PO) circuit at EHF band mmWave frequencies. The combined PO circuit schematic is running based on the Class-E type RF power amplifier (PA) which we described. Theoretical calculations and optimum circuit modeling have been presented [5, 16]. RF oscillation conditions for appropriate circuit schematics have been given [5]. In those works, the first primitive schematic circuit structure had been given by using bipolar transistor [5]. It is the main reference for researchers and developers who want to understand the design concept for Class-E type RF PA-based PO circuits. Mathematical calculations and circuit derivatives were extracted. Standard CMOS technology has been started to use fast. It defined the wireless telecommunication solutions. Customer demands and medical

requests have been raised rapidly depend on the developing technological processes. Integrated solutions became important. For the transceiver circuits, both transmitter (Tx) and receiver (Rx) blocks should be embedded in the same integrated circuit (IC). When both blocks were embedded in the same IC, distortion noise and low-level power sensitivity might be annihilating the Rx signals, since there exist imperfections of isolations between both blocks. This problem might be solved by achieving low power, and high frequency running conditions for circuit blocks. In this work, PO's single nMOS transistor runs at near subthreshold region. The transistor should run as an ideal switch, in which the open circuit current is zero, and the short circuit voltage is also zero. To be able to achieve this condition or approach to do it, basically, transistor ON/OFF, voltage/current characteristics should be lowered. This was achieved in this work. The feedback mechanism is similar to the capacitive feedback mechanism which was designed for Class-EF2 type RF PO except for parallel MOS varactor capacitor between the output node and ground [17]. Serial MOS varactor capacitance from the output through gate input of the nMOS transistor switch was used in this work. A similar feedback capacitance-based PA circuit topology was presented in the previous step. In this step, Class-E type RF PA transistor stress was lessened by lowering the transistor biasing voltage. Similar feedback method was also presented by simply making a short circuit of PA output and transistor gate input [18]. Combined RF PO based on the Class-E type RF PA circuit schematic is given in the next section. Transistor gate inductive coupled biasing was shown in the literature [17]. The same gate biasing methodology was applied in this work. With the emerging CMOS technologies, demands from wireless telecommunication and health care sectors are unexpectedly increasing. Especially the biomedical engineering field has become more popular, since the health-related issue managers are concerned about how to diagnose and treat some dangerous diseases, especially show up most recently. Some authority leaders who are frontiers of related science are thinking about putting mmWave THz RF electronic circuits in important regulatory responsive role. Because electromagnetic waves might be used both for diagnostic and treatment purposes.

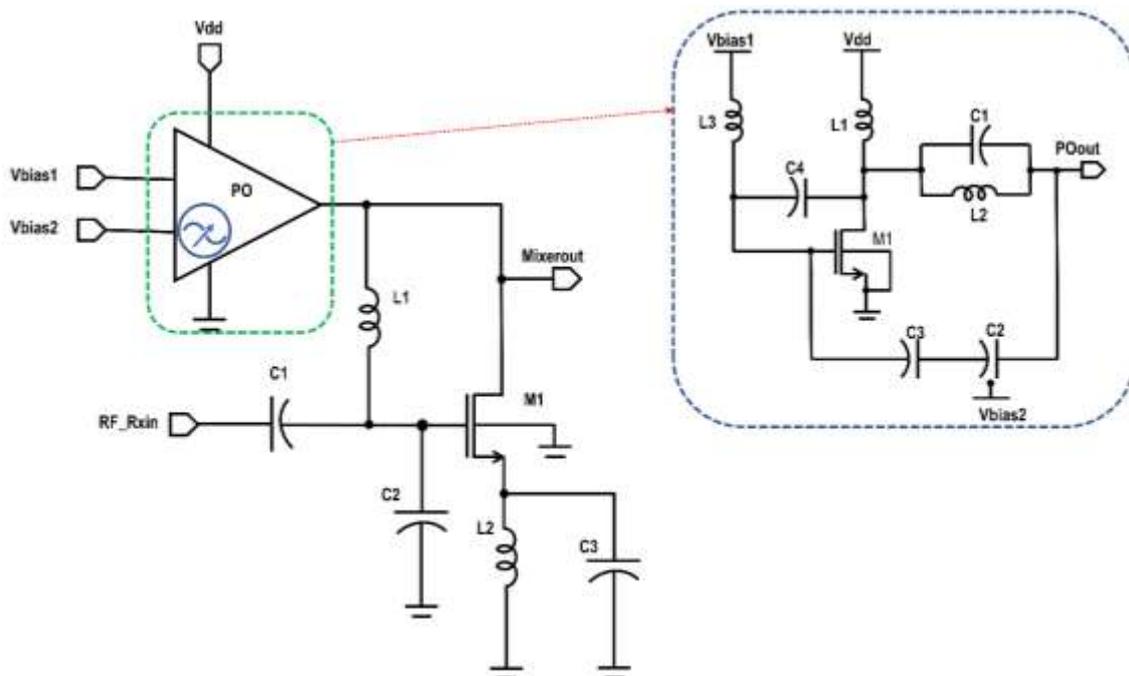


Figure 1. The complete whole Mixer circuit schematic.

For this purpose, to take a responsible attitude, a new RF circuit design methodology was thought and one important circuit which will be used inside the receiver circuit block (Rx) was proposed in this work. In this step, a novel analog electronic architecture RF mixer circuit was designed, and schematic test circuit simulations were performed. In literature, most of the implemented mixer

circuit structures is commonly used single or double-stage harmonic balanced Gilbert cell mixer circuits. Gilbert mixer circuits have high impedances between input and output of the circuit structure since they were usually implemented with high input impedance differential amplifier-based circuit topology, usually by using double stages. Hence, the Gilbert mixer circuit structure has been commonly used in literature. Since they are usually used with double harmonic stages, their voltage gain is also high. Outside of our biomedical focus, mixer circuits are usually used inside Rx blocks of RF electronic telecommunication systems. For example, the receiver antenna receives the incoming electromagnetic wave depend on its physical shape, then passes its magnified RF signals through a low noise amplifier (LNA) circuit. LNA is responsible to amplify incoming RF antenna signals with low noise. LNA output signal and LCVCO input signal were mixed at mixer circuit to extract the demanding envelope signal which was requested before and set by playing LCVCO signal frequency. The products of the mixer output signals are up-converted, and down-converted signals. Most of the biomedical engineering applications were demanding down-converted signals, hence low-pass filter (LPF) would be connected cascade to the output of the mixer circuit. General mixer circuit schematic structures were illustrated in the literature which are Gilbert cell, bulk-driven, and folded mixer circuits [19]. Single and double-stage balanced mixer architectures were given in detailed [20-23]. A compact design concept similar to our approach was also given [24]. RF-DC converters were also evaluated [25]. Band-pass filters were also tested for RF blocks. [26]. The switching element is active n-channel 1V RF nMOS MOSFET integrated into 0.13 μm standard CMOS technology. The complete whole Mixer circuit schematic is illustrated in Figure 1.

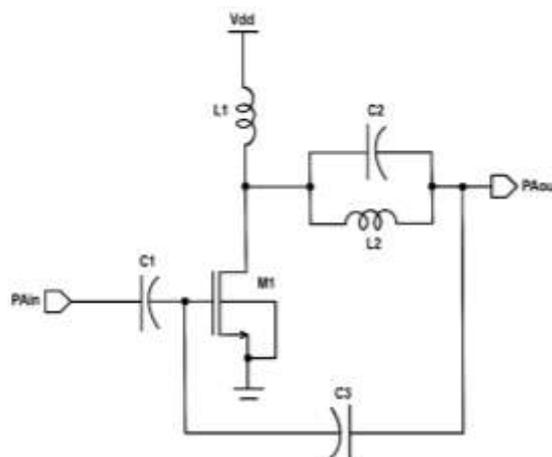


Figure 2. Class-E Type RF Power Amplifier (PA).

The new class-E type RF Power Amplifier (PA) circuit schematic can be seen in Figure2. The class-E Type RF Power Amplifier (PA) test circuit schematic with antenna is shown in Figure 3.

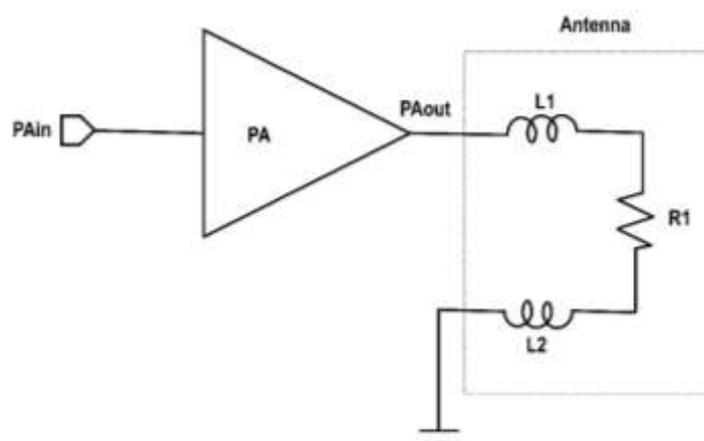


Figure 3. Class-E Type RF Power Amplifier (PA) test circuit schematic with the antenna.

2.2. RF Power Oscillator (PO) Circuit

The schematic circuit of RF PO is illustrated in Figure 4. It has the Class-E type RF PA structure at the circuit core which was shown in the previous section. In this step, extra MOS varactor capacitance was added as labeled by C2. Instead of serial capacitance, the parallel capacitance was used in literature similarly before [18]. Transistor gate inductive biasing has also been done in literature [18]. The two key elements are the L2-C1 parallel LC combination from transistor drain to PO output and C4 gate-drain capacitance. L2-C1 serial output combination structure has been also shown in the previous step. Without using C4 gate-drain capacitance 12-13 GHz but high-power consuming PO output was achieved. With using C4 gate-drain shunt capacitance, over 33 GHz PO output was achieved by consuming low energy. RF Power Oscillator (PO) test circuit is shown in Figure 5.

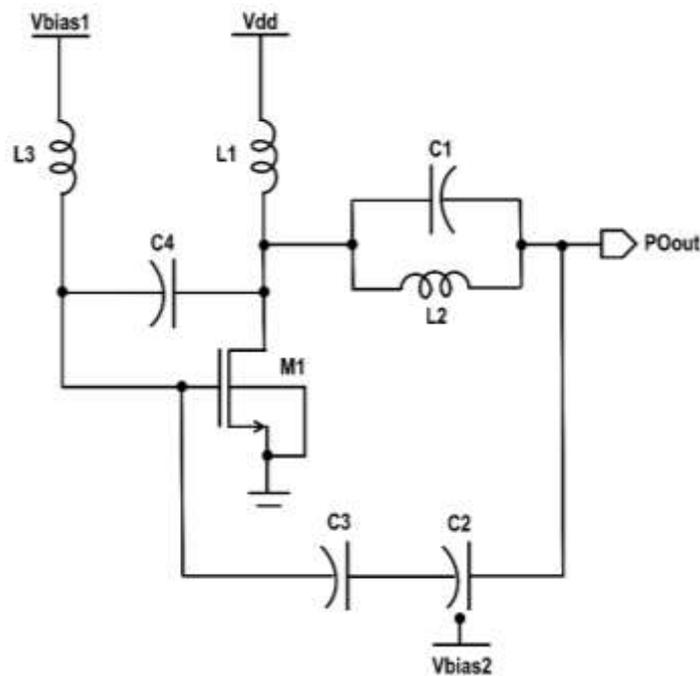


Figure 4. RF Power Oscillator (PO).

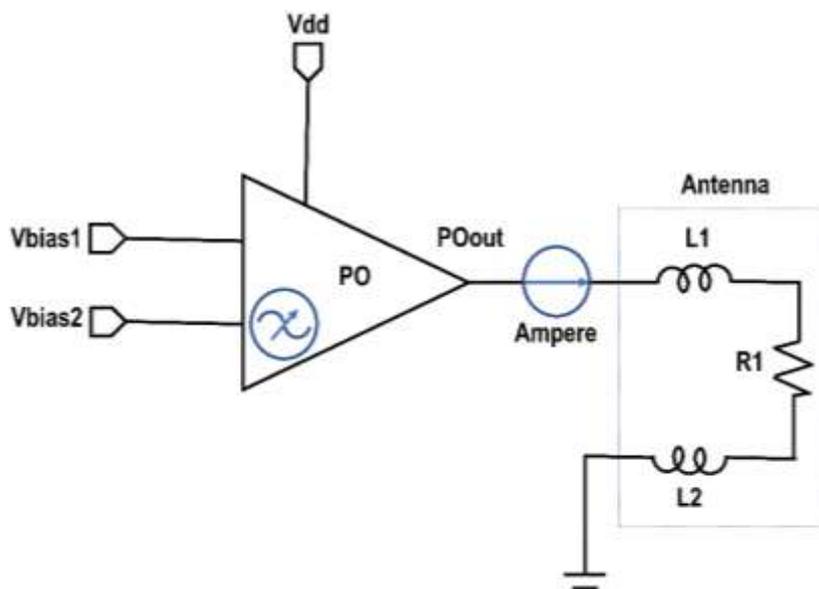


Figure 5. RF Power Oscillator (PO) test circuit.

2.3. RF Mixer Circuit

The novel RF Mixer circuit is shown in Figure 6. It has one power oscillator (PO) which was given in the previous step, one single n-channel MOS (nMOS) 1 V 130 nm technology RF transistor, and passive elements. RF PO circuit was also demonstrated in Figure 4. Voltage, current, and required oscillation signal are supplied by PO for the mixer circuit as seen in Figure 6. By using this method, separate DC supply and LCVCO were eliminated. PO is both supplying necessary voltage, current, and required baseband oscillation signal, prominently. From a different point of view, a low noise amplifier (LNA) circuit can also be seen from the mixer circuit in Figure 6, since M1 and all passive elements are building LNA block. Someone might think of the circuit is the whole receiver (Rx) block except, there is no output buffer. It is the whole Rx schematic circuit.

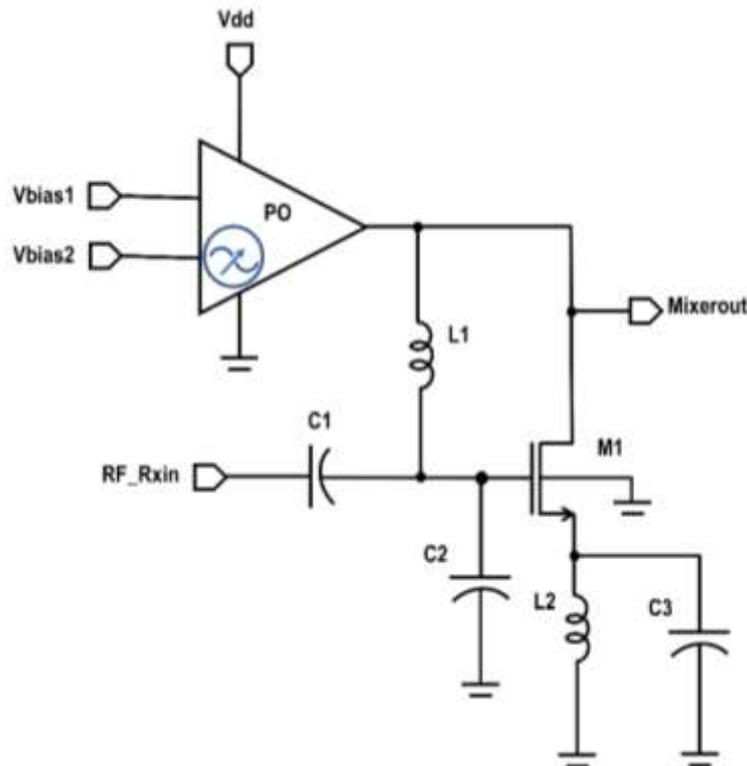


Figure 6. RF mixer circuit.

3. Simulation Results

Spectre simulation program was used. PA input, output voltages, and output current are shown in Figure 7. 300 mV_{pp} AC voltage was applied input of the test circuit which is shown in Figure 7. V_{pp} output voltage is observed as seen in Figure 7 with the dashed red line. 25 mA DC current was pushed through load which can be seen with light magenta color. We also calculated the power-added efficiency (PAE) at 33 GHz input frequency for -8.5 dBm power input variable with 40 harmonics and 15 steps at shooting harmonic balance mode. Simulation output can be seen in Figure 8.

The test circuit was set according to the schematic which is shown in Figure 5 for PO. Vdd and vbias1 supply and bias voltages were set to 600 mV. For mixer test circuit schematic in Figure 6 was set. PO signal outputs were obtained as seen in Figure 9. The total power consumption and current were recorded based on the average root-mean-square (RMS) values. 8.94-milliwatt (mW) power and 14.9 milliampere (mA) rms current were delivered from supplies at 35.6 GHz RF power oscillation frequency.

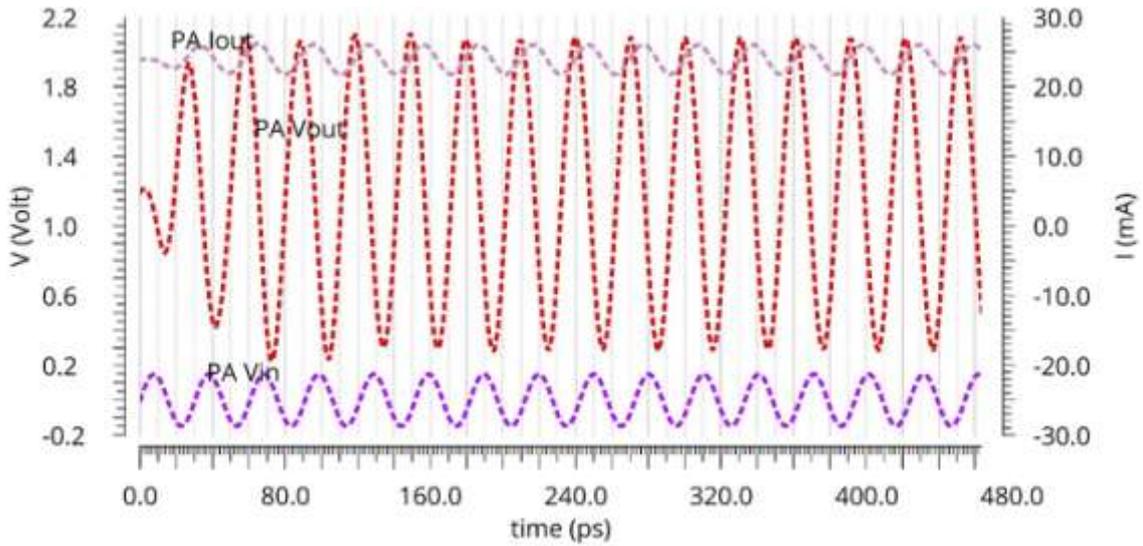


Figure 7. PA output voltage red dashed-line, PA output current light magenta, PA input voltage magenta dashed line.

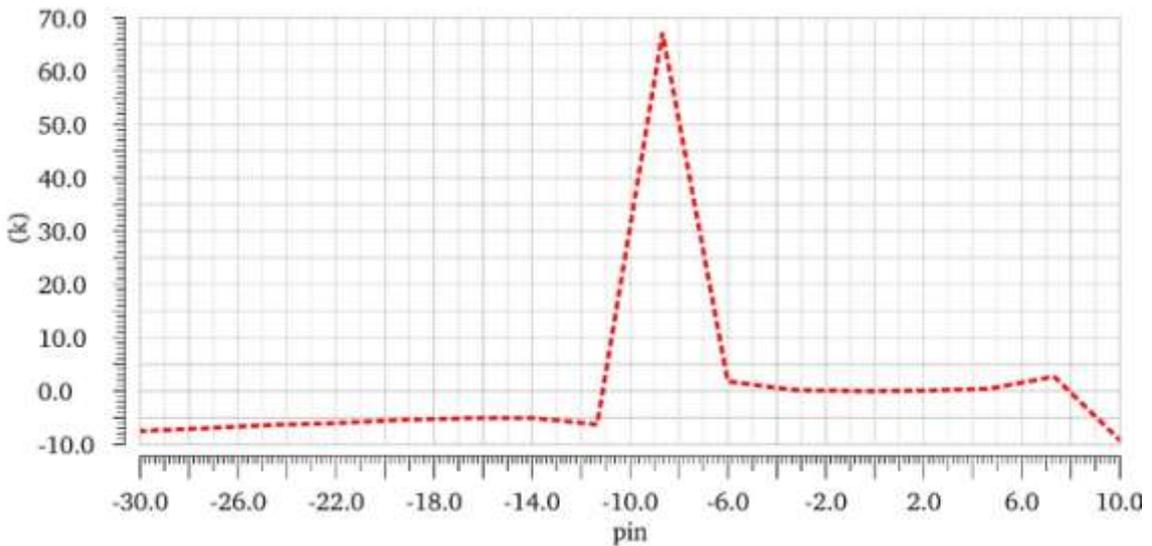


Figure 8. Power-added efficiency (PAE) at 33 GHz input frequency for -8.5 dBm power input variable for 40 harmonics and 15 steps.

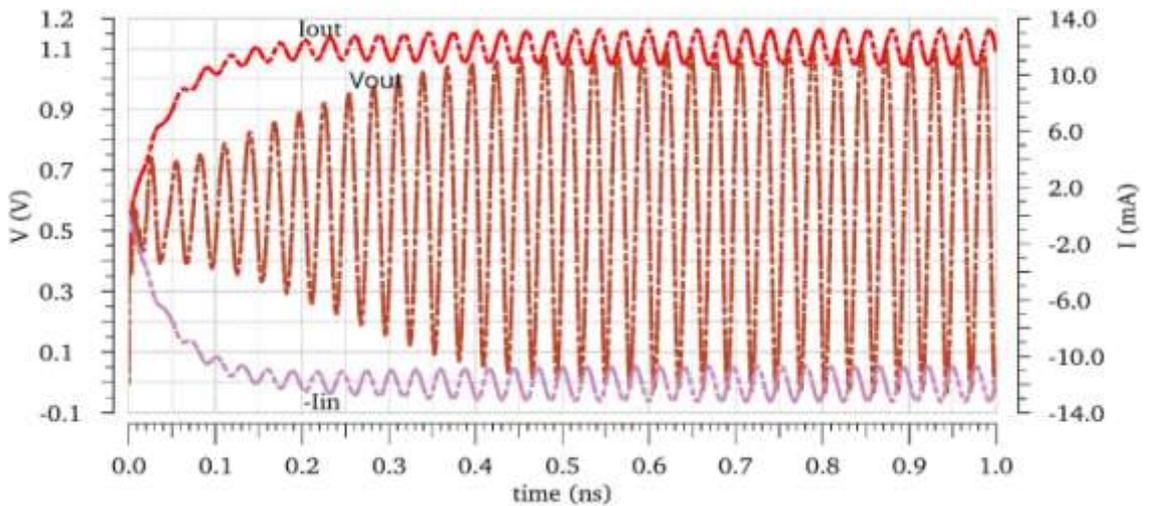


Figure 9. PO output voltage V_{out} , PO output current I_{out} , PO input current I_{in} .

This is the first study, which generates mmWave EHF band (30-300 GHz) RF power oscillation with a single transistor. 35.56 GHz frequency PO signal and 34 GHz RF test signal was mixed, and 3.12 GHz 2nd harmonic envelope signal was extracted as seen in Figure 10.

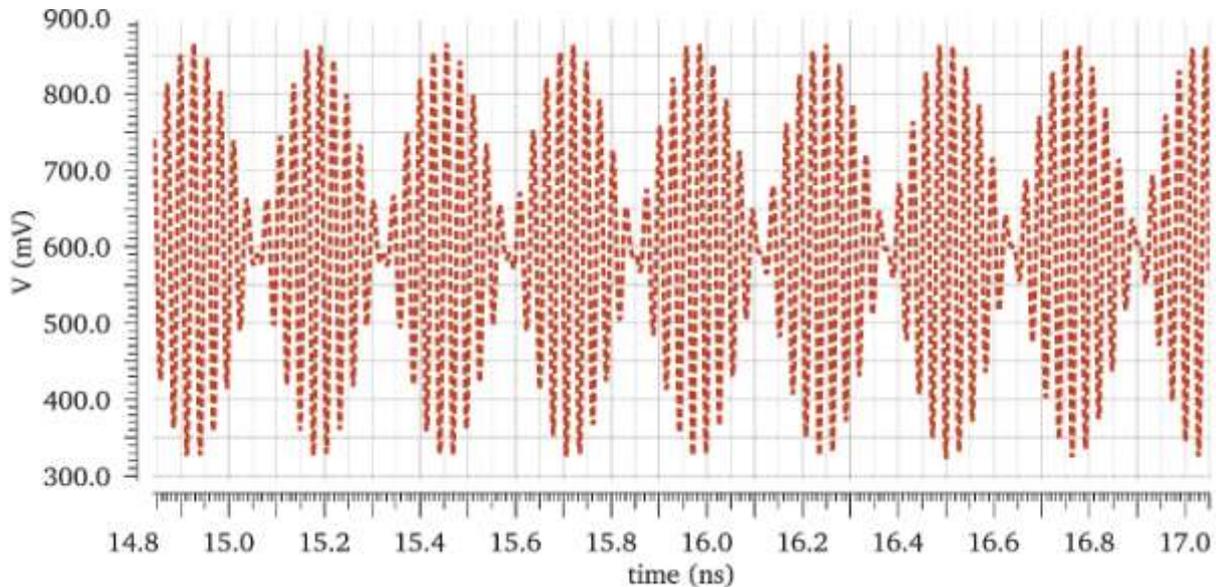


Figure 10. Mixer voltage output signal.

4. Discussion

In this work, RF circuit schematic blocks were designed, implemented and simulation results were presented. PA circuit topology yielded better voltage and current output performance compared to traditional circuit topology which usually uses shunt capacitance. In the future, novel PA circuit schematic topology might be used especially at the transmitter (Tx) side of RF wireless communication and biomedical engineering field systems. In this step, a mismatch circuit network was also eliminated since the feedback capacitance also built a mismatch network. Mismatch circuits bring extra power dissipation to the RF circuits; hence it is good to eliminate mismatch networks. This circuit can be used in wireless communication systems, and low-power biomedical imaging applications such as non-invasive glucose measurement systems at the Tx blocks of RF integrated circuits (RFICs). RF PO circuit was designed, and schematic circuit simulation results were presented. RF PO is running over 33 GHz. EHF band mmWave RF signal generation issue is the most demanding electronics engineering issue with the increasing number of requests from real-world applications for especially indoor wireless telecommunication and biomedical engineering fields. Integrated low energy consuming, high power transfer rate PO structures will become especially important Tx block circuits in near future. In this work, since we have designed the complete integrated PO circuit structure, it has the maximum power efficiency, and power transfer rates better than existing circuit topologies. Since the Class-E type PA circuit reference was confined inside the unique literature reference before, no big scientific research progress has been achieved until now. By simply changing the passive element combinations and adding extra capacitance between transistor gate-drain nodes, it was achieved to have better results in this work.

5. Conclusion

A compact RF Mixer circuit which runs in EHF band mmWave frequency was proposed. If the proposed work has the output buffer, it might be evaluated as a complete receiver Rx block of the EHF band RF circuit. But since the proposed work mostly focused on how the envelope of Rx input signal is extracted, mixer circuit topology was brought into account. In future circuit schematic

designs, a complete Rx circuit block with the output buffer will be designed and implemented. Circuit analyses will be demonstrated for the complete Rx circuit block.

Authors' Contributions

HOK wrote up the article, read and approved the final manuscript.

Conflict of Interest

There is no conflict of interest

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