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Research Article

Design of a High Linearity 6-GHz Class-F Radio Frequency Power Amplifier

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Abstract: In this study, a high linearity class-F RF power amplifier is introduced. It is designed to operate at a frequency of 6 GHz with a bandwidth of 400MHz. The amplifier mixes between the characteristics of conventional switch mode class-F and class B amplifiers. It is biased at very low quiescent power, thus it dissipates negligible DC power in the absence of RF excitation. This makes it suitable for handset applications. The amplifier is designed and tested on Microwave Office Environments. It showed linear input/output characteristics for an input RF power range of -20 to 5d Bm. The amplifier collector efficiency is 80%, which is greater than that of ideal class-B power amplifier. In addition, it is sensitive to amplify low level RF signals, therefore it needs no preamplifier.

Keywords: Amplifier linearization, class-F amplifier, RF Power amplifier, switching amplifier

INTRODUCTION

The challenge facing engineers working in electronic communication fields, is to design high output power, high efficiency, broad bandwidth and high linearity RF power amplifiers operating in multiple frequency bands and various modulation standards (Chen and Peroulis, 2011, 2012; Huang *et al*., 2010; Pornpromlikit *et al*., 2010; Cho *et al*., 2013; Moon *et al*., 2010). In many applications, parallel power amplifiers are used as a solution for involving multiband signals and this will results in increasing area, complexity and cost (Johansson and Fritzin, 2014). Class-F RF power amplifier represents a good solution to this problem (Johansson and Fritzin, 2014; Fritzin, 2011; Grebennikov *et al*., 2012; Huang *et al*., 2010; Skaria, 2011).

Class-Fpower amplifier generates multiple harmonic components in the drain or collector voltage of its active device (Skaria, 2011; Grebennikov *et al*., 2012). The drain or collector current flows during very low (approximately zero) drain or collector voltage, while drain or collector voltage is high (approximately twice the DC source voltage) during zero drain or collector current (Grebennikov *et al*., 2012). This minimizes greatly the power dissipated by the switching device and increases the power amplifier efficiency (Weber, 2001; Pozar, 2012). Class Famplifiers based on peaking of odd harmonics, have drain or collector currents containing even harmonics only. Consequently, for better design, the input impedance of the load circuitry should behave to some extent as an open circuit at odd harmonics and approximately as a short circuit at even harmonics (Weber, 2001; Grebennikov *et al*., 2012; Pozar, 2012).

Class-F RF power can be designed using third harmonic peaking method. In this method, the load network comprises a parallel L_0C_0circuit resonating at the operating frequency f_0 and a parallel L_3C_3 circuit resonating at the third harmonic ($3f_0$) (Rogers and Plett, 2003). The parallel resonator $L_0C_0$is shunted by the load resistor and the parallel combination is connected in series to L_3C_3resonator. In this configuration, the third harmonic component suffers an open circuit due to the third harmonic resonator, thus nothing of this component approaches at the amplifier output terminal (Weber, 2001; Grebennikov *et al*., 2012; Pozar, 2012). In addition, all the higher odd harmonic components are attenuated greatly due the fundamental frequency resonator (Rogers and Plett, 2003).

Another technique employing quarter-wavelength transmission line is utilized to design a class-F RF power amplifier. In this design, the third harmonic resonator is replaced by λ/4 transmission line (Rogers and Plett, 2003; Johansson and Fritzin, 2014). Where, λ represents the wave length of the electrometric wave at the amplifier operating frequency. The λ/4 transmission line offers open circuit to all odd harmonic components generated at the drain or collector of the power transistor involved in the power amplifier circuitry (Johansson and Fritzin, 2014). For ideal operation of this configuration, the drain or collector voltage of the output transistor is flat voltage of magnitude of twice the DC source voltage during OFF state of the transistor and zero during the ON state (Rogers and Plett, 2003; Johansson and Fritzin, 2014).

The loading networks in class-F power amplifiers, serve matching to fundamental frequency and tuning harmonic components simultaneously, in addition to reduction in the number of circuit elements and overall circuit size (Beltran, 2014; Kim *et al*., 2015). The main drawback of the switched power amplifiers, is the lack of linearity in amplitude between input and output signals and the difficulty in fabricating the λ/4 transmission line for class-F RF power amplifier (Johansson and Fritzin, 2014).

Since the conventional class-F RF power amplifier is one of the switch mode power amplifiers, its 1-dB compression point is reached before the amplitude of its output voltage amplitude approaches the DC source value, thus it shows nonlinear behavior between the input and the output signals (Rogers and Plett, 2003). To compensate for nonlinearity for such kinds of power amplifiers, additional techniques should be adopted (Cripps *et al*., 2009; Huang *et al*., 2010). In this study, a 6-GHz class-F RF power amplifier is introduced. The proposed amplifier is designed such that it keeps on linearity until the amplitude of the output RF signal approaches magnitude of the DC source voltage.

MATERIALS AND METHODS

The schematic design of the proposed class-F power amplifier is shown in Fig. 1. This amplifier is driven by a DC source V_{CC} of 4 volts. It is designed to operate at an RF frequency f_0 of 6 GHz with a bandwidth B.W of 400MHz. In this design, C_2, C_3 are very large capacitors (real short circuits at the operating frequency), while the radio frequency chokes RFC_1 and RFC_2 represent open circuits at the operating frequency.

The proposed amplifier is biased at low quiescent collector current of 0.25 mA. The bias circuit composed of R_1 and R_2 is designed such that it draws a DC current of 0.25 mA from V_{CC}. In the absence of RF excitation, the total bias current drawn from the DC source is o.5 mA, thus, the amplifier quiescent power is limited to 2 mW. This low bias power makes this amplifier suitable for handset applications. Biasing this amplifier (even at low bias current) makes it sensitive to low level RF signals, thus, no preamplifier is needed to operate it. The behavior of the proposed amplifier mixes between class-F and class-B characteristics. Figure 2 shows the schematic design of the proposed amplifier carried out on Microwave Office Environments using "BFP620" RF power transistor.

The LC circuit composed of L_0 and C_0 is designed such that it resonates at 6 GHz with a quality factor Q of 15. Assuming that, the impedance of the output port is 50Ω, then L_0 and C_0 can be determined by:

$$L_0 = \frac{50}{2\pi f_0 Q} \quad (1)$$

$$C_0 = \frac{Q}{100\pi f_0} \quad (2)$$

Assuming that, the input impedance of the power transistor Q_1 is $Z_i = R_i + jX_i$, then the matching circuit

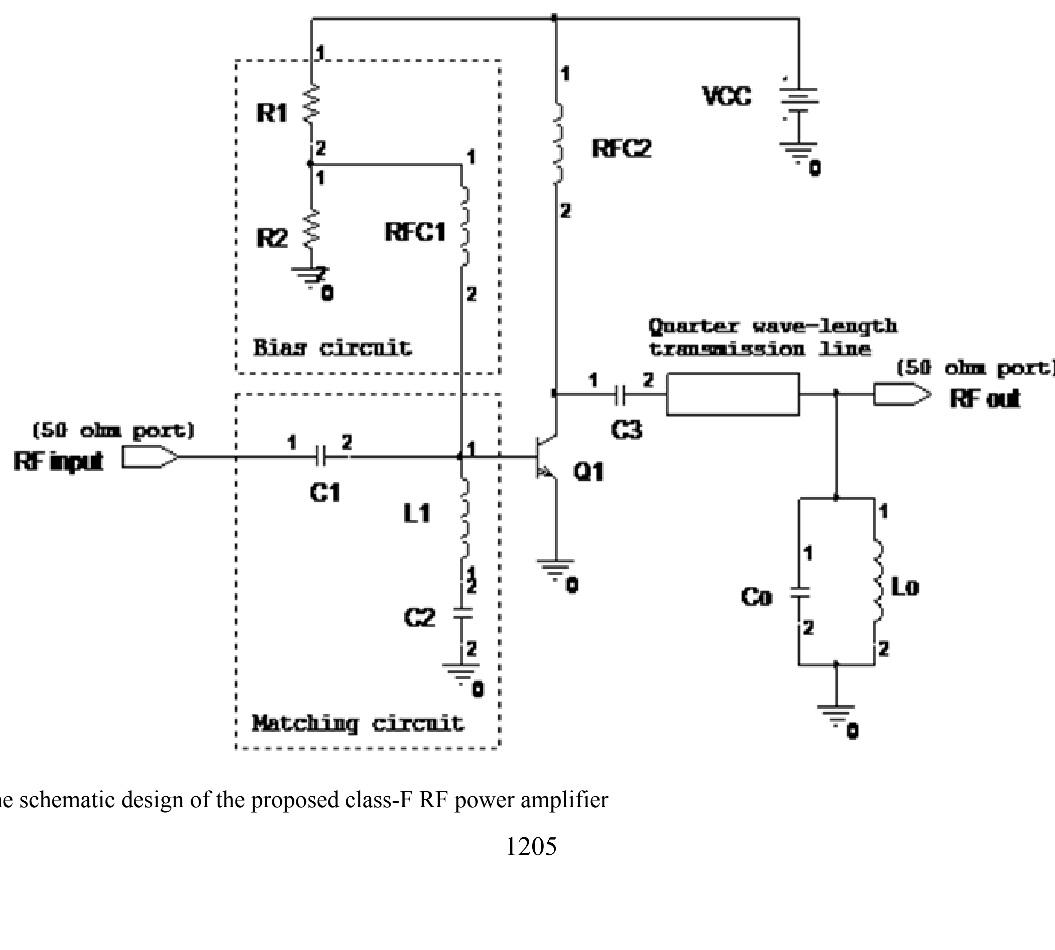


Fig. 1: The schematic design of the proposed class-F RF power amplifier

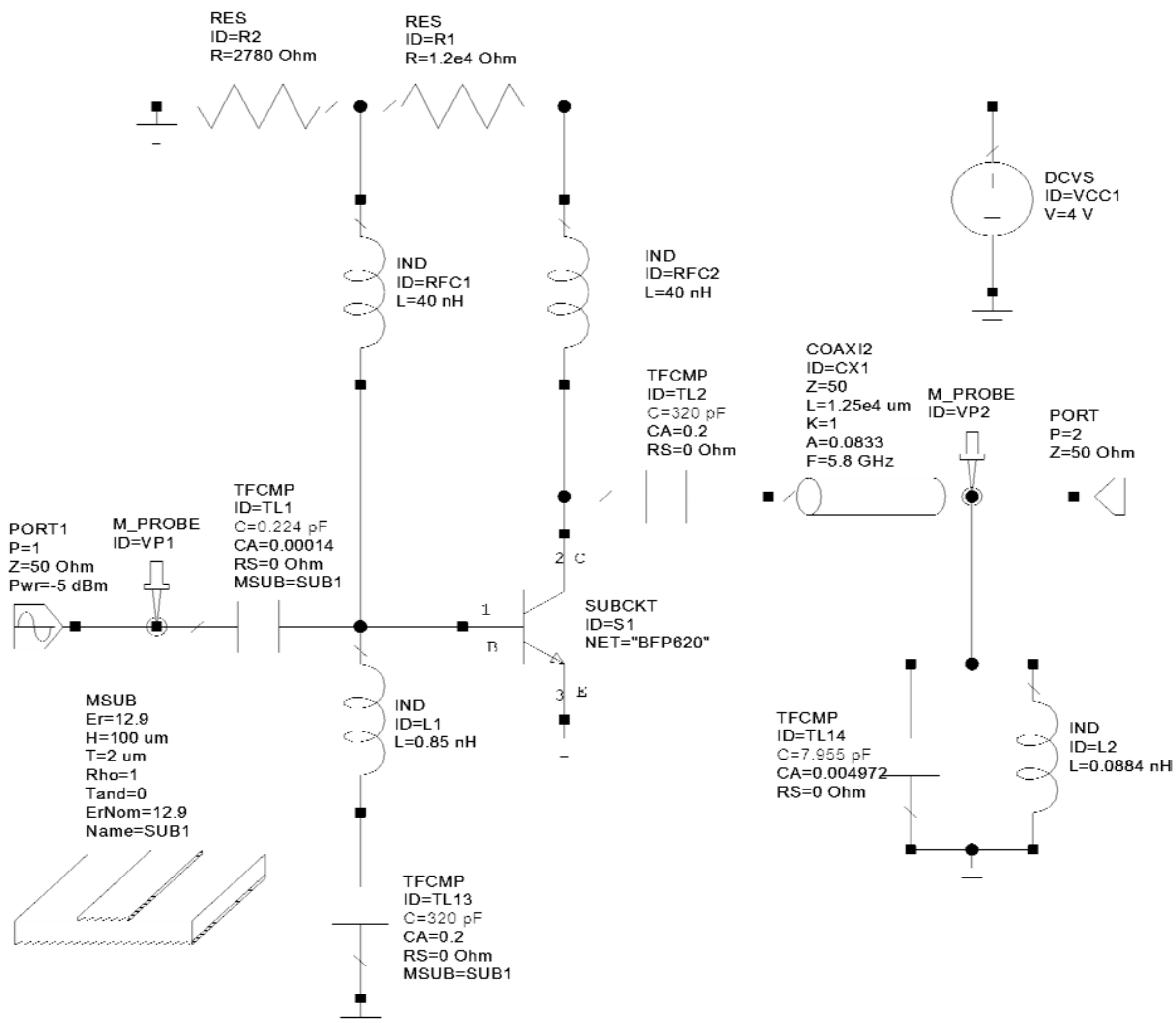


Fig. 2: The proposed amplifier circuit design using microwave office environments

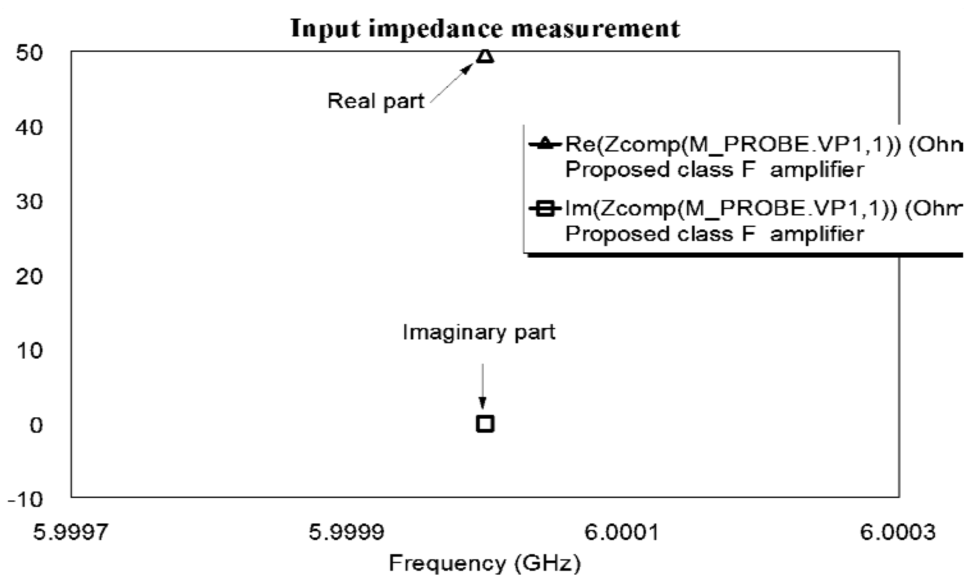


Fig. 3: The input impedance of the proposed amplifier with matching circuit

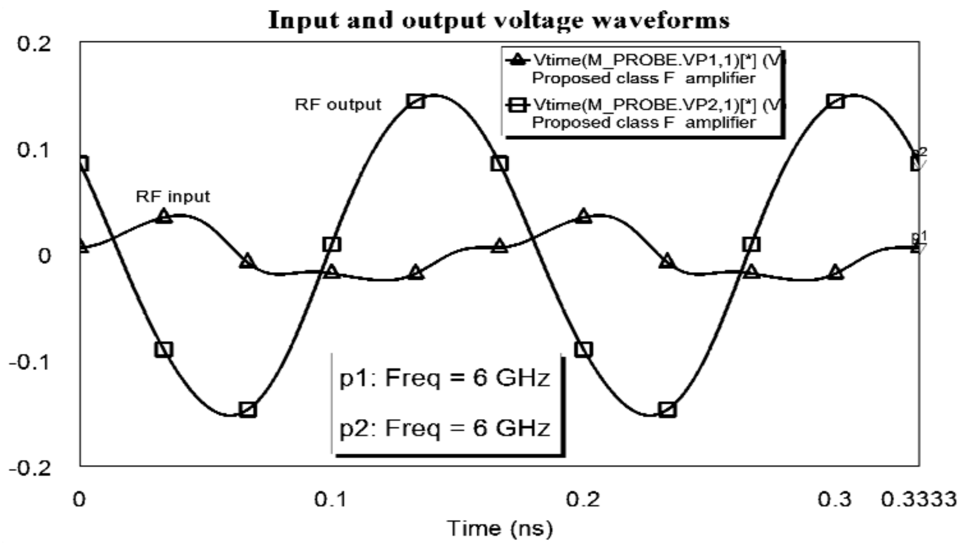
is designed such that its output impedance matches Z_i and its input impedance matches Z_0, which is equal to 50Ω.. According to Equations (1) and (2), L_0 and C_0 are determined as 0.0884nH and 7.9545pF, respectively. The transmission line length (λ/4) = 12500 μm. Using a forward current gain *β* of 425 for the transistor BFP620, R_1 and R_2 are determined as 12000Ω and 2780Ω, respectively.

RESULTS AND DISCUSSION

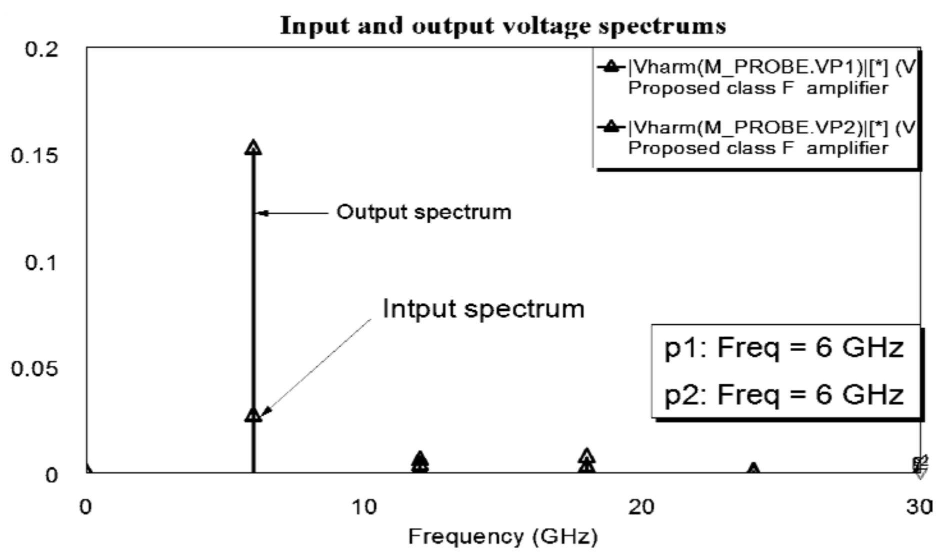
The proposed design shown in Fig. 2 was operated on Microwave Office Environments for identifying the parameters of the matching circuit and verifying its linearity. C_1 and L_1 were tuned such that the input of the matching circuit matches 50Ω input port. C_1 and L_1 were tuned to 0.221pF and 0.85nH, respectively.

The input impedance of proposed amplifier with matching circuit was measured as shown in Fig. 3, which indicates a real part of 50Ω and imaginary part of zero value.

An RF input power of -20dBm was applied first at the input port of the proposed amplifier. Figure 4a shows the input and the output voltage waveforms, while Fig. 4b shows their corresponding spectrums. The spectrum components of the input and output voltages at the fundamental frequency reveal a voltage gain of about 6.5.

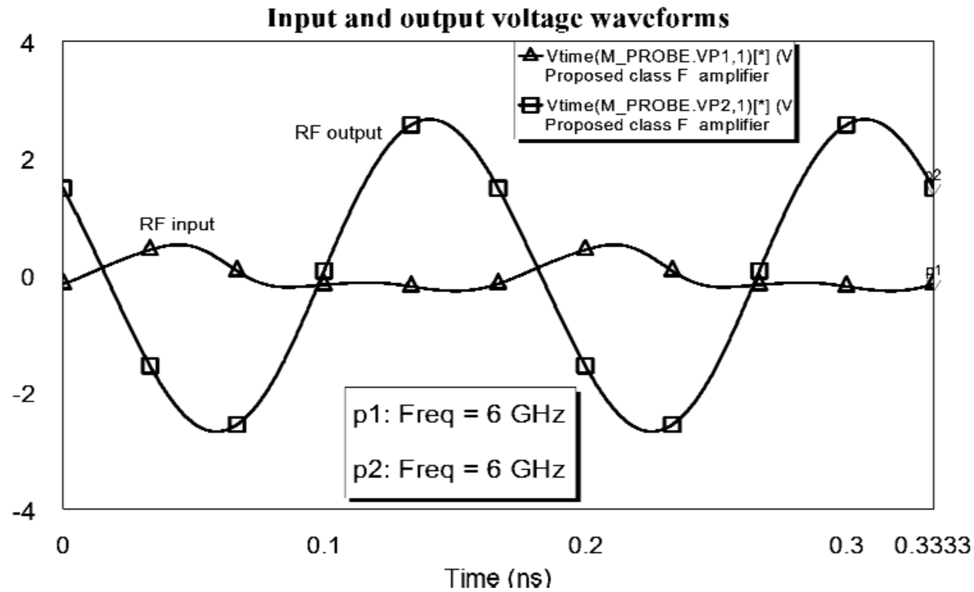


(a)

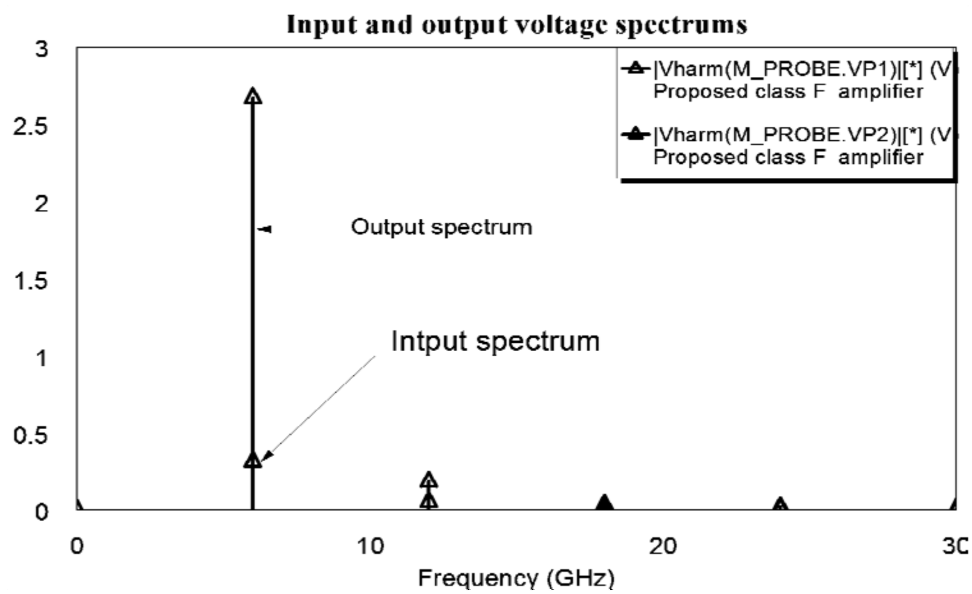


(b)

Fig. 4: Input and output voltages for an RF input of -20dBm; (a): actual waveforms and; (b): their spectrums



(a)



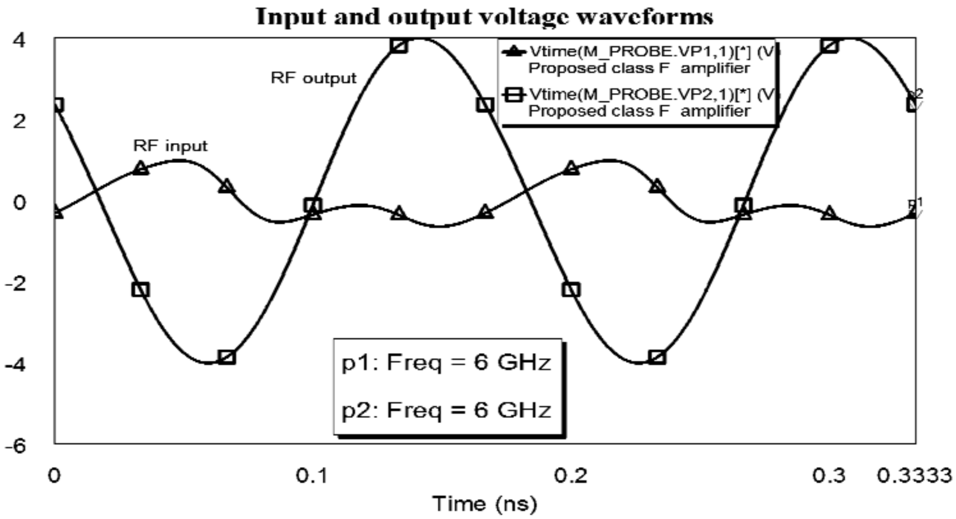
(b)

Fig. 5: Input and output voltages for an RF input of 0dBm; (a): actual waveforms and; (b): their spectrums

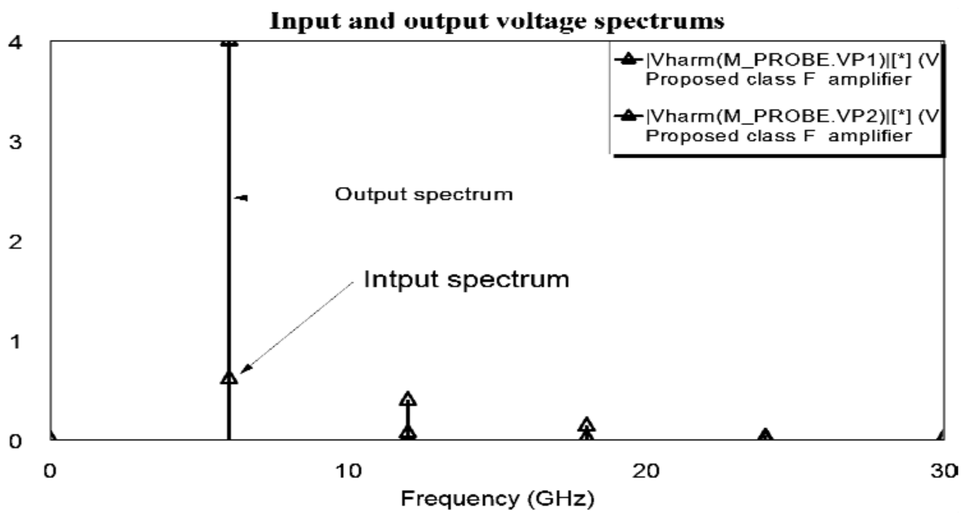
Figure 5 shows the input and the output voltage waveforms and their corresponding spectrums for an RF input power of 0dBm, while Fig. 6 corresponds to test results of an input RF power of 5dBm. The spectrum components of Fig. 5 and 6 reveal voltage gains of 7.3 and 6.8, respectively.

The upper tests show that, the voltage gain at the fundamental frequency is varying within 6.5 to 7.3 for an RF input power range of -20dBm to 5dBm. This means that the voltage gain of the proposed amplifier is almost constant, or in other words it reveals linear relationship between its RF input voltage and RF output voltage. In addition, the amplifier output voltage contains negligible harmonic components. The input output power test or AM-AM test is shown in Fig. 7. The figure shows linear output power for input power range of -20dBm to 5dBm.

For an RF input power of 5dBm, the amplifiers draws an average DC current of 50mA from DC source, while an RF output voltage having an amplitude of 4V is delivered to a 50Ω output port. Thus, the DC input power is 50mA×4V = 200mW and the RF output power is $(4V/\sqrt{2})^2/50\Omega$ = 160mW. This yields a collector efficiency of 80%, which is greater than that



(a)



(b)

Fig. 6: Input and output voltages for an RF input of 5dBm; (a): actual waveforms and; (b): their spectrums

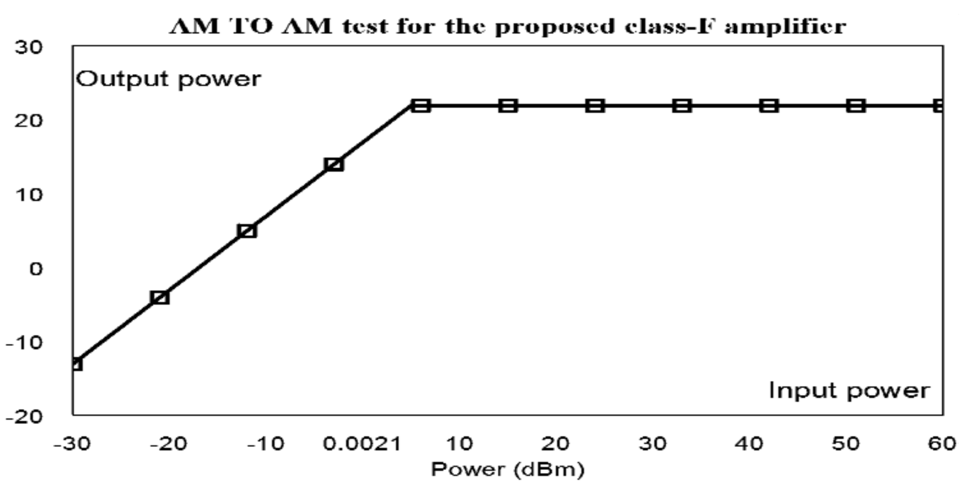


Fig. 7: Input and output power test (AM-AM test) for the proposed amplifier

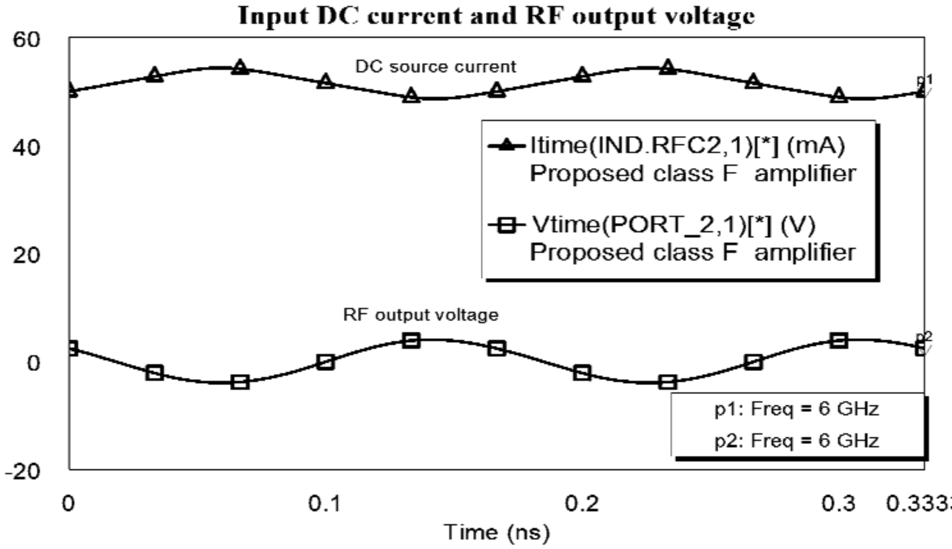


Fig. 8: DC source current and RF output voltage for an RF input of 5dBm

of ideal class-B amplifier (Rogers and Plett, 2003). The input DC current drawn from DC source and the RF output voltage for an RF input power of 5dBm is shown in Fig. 8.

CONCLUSION

It is verified that the proposed amplifier has almost constant voltage gain for an input excitation varying in the range of less than 25 mV up to slightly greater than o.5V. In the absence of RF excitation, the amplifier consumes negligible power from the DC source, thus this makes it suitable for handset applications. The amplifier is capable of producing an RF output voltage of amplitude of 4V, which is equal to the DC supply voltage V_{CC}. It can amplify an RF input power less than -20dBm and keep on its linearity up to an input RF power of 5dBm. In addition, the proposed class-F amplifier reveals a collector efficiency of 80%, which is greater that of ideal class-B amplifier.

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