Noise and Power Optimization of a MMIC Quasi-Circulator

Ahmed Gasmi, Bernard Huyart, *Member, IEEE*, Eric Bergeault, *Associate Member, IEEE*, and Louis Jallet

***Abstract*—This paper first sums up the power and noise limits of various types of active circulators and quasi-circulators. It then presents the design and measured performances of a narrow-band quasi-circulator module tailored for use in a transmit/receive (T/R) module. Its design implements an active power divider and a combiner. A method to calculate the minimum noise figure is presented for this circuit. At 4 GHz, the device demonstrates a noise figure of 5.5 dB and an output power of 18 dBm with associated gains of 4 and 7.6 dB for the receive and transmit path, respectively. The third-order intercept point (IP3) is equal to 25.6 dBm for the transmit path.**

***Index Terms*—Active circulator, MESFET, MMIC, noise.**

I. Introduction

CIRCULATORS have many applications in microwave systems such as the separation of transmitted and received signals, realization of phase shifters [1], telecommunications multiplexing, and demultiplexing canals, etc.

The development of active integrated circuits using the nonreciprocity of transistors has allowed us to realize circulators [1], [3]–[14]. Active circulators offer an alternative approach to ferrite miniature circulators [2] with potential advantages in small size, light weight, and compatibility with monolithic-microwave integrated-circuit (MMIC) technology. However, the drawbacks of active circulators over their ferrite counterparts are that transistors require dc bias, which introduce excess noise and limit the RF power-handling capacity of the circulators.

At present, many papers concerning active circulators stress frequency bandwidth and scattering parameters (i.e., insertion and return losses, isolation). To our knowledge, there are no previously published results concerning an active device allowing one to simultaneously transport a high-power signal from transmitter to antenna and a weak-power signal from antenna to receiver. This problem has been studied by Katzin [3], but his paper successively describes the performances of two different circulators. One presents a noise figure greater than 8.5 dB and an insertion loss of 2 dB, while the other one gives an output power of 1 W, but with a 12-dB noise figure in the receive path.

In this paper, we propose a circuit allowing one to simultaneously optimize the noise figure and the available output power of an active quasi-circulator. The analyzed frequency band is 3.8–4.2 GHz.

Section II presents different designs of active circulators and gives arguments about their power-handling capability and noise figure. Section III gives the theoretical calculation of the noise figure of the antenna–receiver ports. Section IV emphasizes power output of the transmitter antenna path. Section V shows the experimental results of the active quasi-circulator. Scattering parameters are presented in the frequency band of 3.8–4.2 GHz. The noise figure, the input output power characteristics, and the intermodulation product third-order intercept point (IP3) are given at the center frequency of 4 GHz.

II. Active Circulator Design

The first circulator was realized with three bipolar transistors in 1965 by Tanaka *et al*. Its operating frequency is approximately several kilohertz [4]. This circuit topology has been reproduced in MMIC technology using three conventional FET's tied together by their sources [5]–[7] with maximum frequency operation of 10 GHz [6]. A passive or active common-source resistor [7] allows interaction between the FET's. Moreover, device symmetry is essential to achieve effective circulation. Even if the FET's are low-noise transistors, the common feedback resistance cause high noise figure. In all cases, this configuration, using three identical FET's, and cannot simultaneously achieve high-power and low-noise characteristics of a circulator used in a transmit/receive (T/R) duplexer. The circulator using three dual-gate FET's [8] has the same topology as the above-mentioned circuits [4]–[7] and then it will have an important noise figure. The other drawback is that the circuit presents low-output power capability.

A second way is to design active circulators using power dividers [9], [10], or couplers [11] and amplifiers which act as isolators. A different combination permits true circulators to be obtained, since all ports are interchangeable or quasi-circulator modules (QCM's). In this last case, there is only circulation from port 1 to port 2 and from port 2 to port 3. Compared to true circulators used in T/R duplexers, the QCM's isolate the transmitter and receiver even in the presence of reflected signals from the receiver. The QCM consists of a Wilkinson power divider [10] and power and low-noise amplifiers. The drawbacks of this configuration are: 1) half of the output power is dissipated by the 100-Ω resistor of the Wilkinson divider and 2) the noise figure of the receiver path is twice the noise figure

Manuscript received October 19, 1996; revised May 19, 1997.

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Publisher Item Identifier S 0018-9480(97)06060-2.

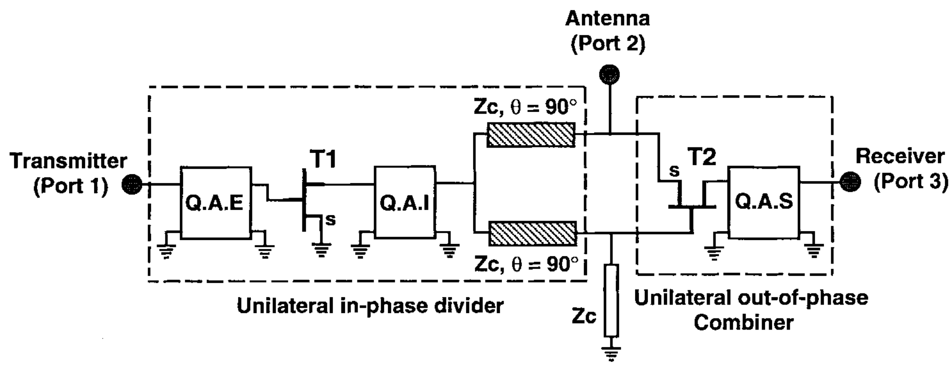


Fig. 1. Block diagram of the quasi-circulator module.

of the low-noise amplifier. Moreover, the thermal noise of the 100-Ω resistance still degrades the total noise figure.

A third category of active circulators use a unilateral divider/combiner. The QCM is generally composed of an active out-of-phase divider (or an active in-phase divider), an active in-phase combiner (or an active out-of-phase combiner), and a shunt impedance equal to the reference impedance in order to preserve the symmetry. Different strategies are applied to obtain an active divider/combiner. Some designs are based on line-unified FET (LUFET) and transitions between slotlines and coplanar waveguides [12]. Other designs are based on a conventional foundry high electron-mobility transistor (HEMT) [1], [10] or MESFET [13] structure with coplanar waveguides (CPW's) [1], [10] or microstrip components [13]. Generally, these structures are realized with transistors with large and small gate periphery to design the input divider and output combiner. The output noise sources of the in-phase divider using two identical FET's are not correlated. Thus, their noise sources do not cancel in the combiner, which dramatically degrade the noise figure of the receive path. The out-of-phase divider using a floating-source transistor [12] as a three-port device limits the gain of the transmit path and, therefore, the power-handling capability of the QCM is limited.

The last type of circulator, but actually the first MMIC circulator, requires a delta junction consisting of three non-reciprocal phase shifters [14]. Each phase shifter is achieved by means of a transmission line connected in parallel with a common-source MESFET. The transmission line provides the path for most of the signal energy to travel. The active device only samples a fraction of the voltage from the transmission lines carrying the RF power, amplifies it, and feeds it to the output transmission line with the proper phase. According to the gatewidth of the MESFET's, this circuit can handle high power between the ports. The noise figure of this circuit between two ports depends on the noise generated by the three transistors, and thus it will be important. Moreover, the circuit uses three identical MESFET's and, therefore, it cannot be optimized for use as a T/R duplexer.

By taking into account the previous work already described, we have chosen to realize a quasi-circulator consisting of an active in-phase divider and an active out-of-phase combiner (Fig. 1). In comparison with the circuits presented in [2] and [3], the active in-phase divider contains a common-source MESFET T_1. Indeed, this presents the advantage of transmitting different power signals (low, medium, and high power). The other advantage is that the noise figure of the receive path will be independent of the noise generated by the in-phase divider, as described in the following section. The operating principle of the QCM (Fig. 1) is as follows.

A signal from port 1 gives two in-phase signals to the out-of-phase combiner. A shunt impedance Z_c equal to the reference impedance of port 2 of the QCM is connected to the other port of the in-phase divider in order to have the same magnitude of the signals to the out-of-phase combiner. These two signals will be completely canceled by the combiner. Therefore, the incident signal does not appear at port 3 $(S_{31} = 0)$. One part of the divider output signal is available at port 2 of the QCM. The divider is an active element so that we can obtain a gain G_1 from port 1 to port 2, thus $S_{21} = G_1$. $S_{12} = 0$ because the divider is unilateral.

On the other hand, by connecting a generator at port 2 and due to both 90° phase shifters, two out-of-phase signals will be available at the input ports of the combiner. These signals are added by the active combiner, and then $S_{32} = G_2$ (gain of the second stage). The combiner is unilateral, thus $S_{23} = 0$. In the same way, we can conclude that $S_{13} = 0$ because the two ports are linked by two nonreciprocal devices (divider and combiner).

The divider is achieved by using a common-source transistor T_1, a matching two-port quadripôle d'adaptation d'entrée (QAE) at port 1, an interstage matching two-port quadripôle d'adaptation intermédiare (QAI), and a junction made of two 90° phase shifters. The combiner consists of a transistor T_2 and a matching two-port quadripôle d'adaptation de sortie (QAS) network at port 3.

III. The Noise-Figure Derivation

Before optimizing the noise figure F_{23} between ports 2 and 3, it is necessary to know its minimum value if the transistor T_2 is a noiseless three-port. For this purpose, we have used a simple model in which the transistor T_2 is represented by its transconductance g_m. Similarly, the noise behavior of the circuit consists of the impedance Z_c (the 50-Ω load at port 1), the transistor T_1 and the two-port QAI has been modelized by

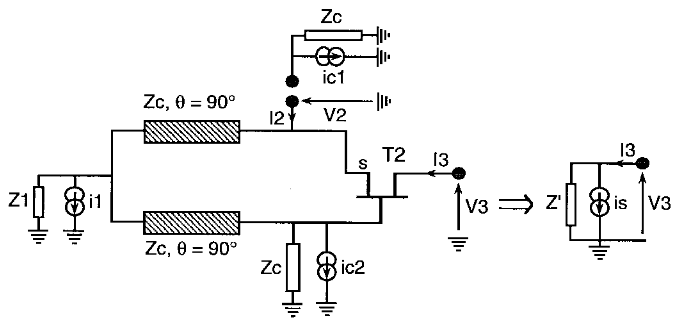


Fig. 2. Simplified circuit configuration to calculate the noise figure F_{23}.

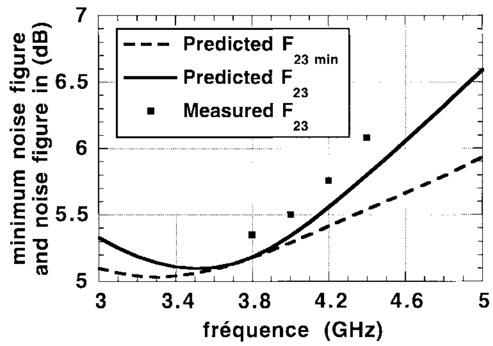


Fig. 3. Predicted and measured noise figure F_{23} and predicted minimum noise figure $F_{23\,\min}$ of the quasi-circulator module.

an output equivalent impedance Z_1 and a noise-current source i_1 (Fig. 2). Moreover, the circuit (Fig. 2) is consists of two other impedances: the load impedance Z_c at port 2 which is at the standard temperature T_0 (290 K), and the shunt impedance Z_c between the divider and combiner which is at the room temperature T_a (300 K). These three impedances generate three noise-current sources i_1, i_{c1}, and i_{c2}, respectively. It is straightforward to calculate the noise current i_s at the output impedance Z':

$$i_s = \frac{g_m Z_c}{1 + g_m Z_c}(i_{c1} - i_{c2}). \tag{1}$$

This result shows that the noise generated by the transistor T_1 has no influence on the receive path, because i_s is independent of the noise source i_1 and impedance Z_1. This result is due to the perfect symmetry of the circuit in comparison with the axis passing by port 1 and port 3 of the QCM. By definition of a two-port noise figure [15], the noise figure F_{23} of the quasi-circulator will be simply expressed as

$$F_{23} = \frac{T_0 + T_a}{T_0}. \tag{2}$$

This equation shows that the QCM noise figure will be greater than 3.1 dB even if the QCM is realized with a noiseless transistor T_2. Owing to the symmetry of the circuit, there is an equal influence of the impedance Z_c of port 2 and of the shunt impedance Z_c. Therefore, one cannot change the shunt impedance Z_c to improve the noise figure F_{23}. The foreseeable solution consists of the cooling of the circuit of the QCM. This leads to decrease in the room temperature T_a of the shunt impedance Z_c. Consequently, the noise figure F_{23} of the QCM will be improved. Another solution is to replace the shunt impedance Z_c, which is at room temperature ($T_a = 300\,\mathrm{K}$), by an active termination—more precisely, by a common-source transistor, which has the gate connected to the drain [18]. This active termination must be chosen so that the impedance between the gate and the source (or between the drain and the source) is equal to 50 Ω. Moreover, the transistor must be biased for low-noise operation. The advantage is that the apparent temperature of the active termination is approximately half of the room temperature. We can thus substitute T_a by $T_a/2$ in (2), which shows that the noise figure of the circuit can be improved by 1.27 dB. In the actual case, T_2 is a transistor of F_{20} technology of GEC Marconi Material Technology (GMMT) foundry with 0.5 × 350 μm^2 gate dimensions and biased at $I_{\rm ds} = I_{\rm dss}/5$, where $I_{\rm dss}$ is the saturated drain current. The calculation of the noise figure F_{23} has been done with the software LIBRA.[1] We have closed port 1 of the QCM by a load impedance $Z_c = 50\ \Omega$. This has led us to calculate the noise figure F_{23} of a two-port network instead of the three-port network. In this case, the two MESFET's T_1 and T_2 are characterized by their specific noise parameters, and that the whole resistances of the circuit have been carried at room temperature T_a (300 K). At the frequency of 4 GHz, the simulated noise figure F_{23} of the QCM is equal to 5.3 dB. This value cannot be improved any further because it is already very close to that obtained for the minimum noise figure $F_{23\,\min}$ which is equal to 5.25 dB (see Fig. 3).

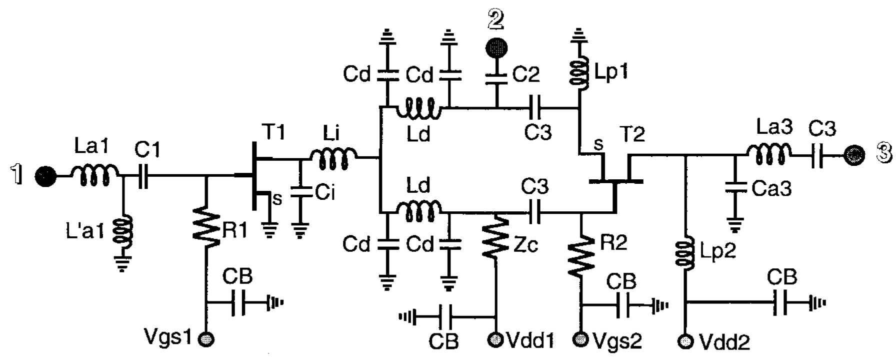
IV. The Power Optimization

The transistor T_1 is a common-source MESFET, with a gate area of 0.5 × 700 μm^2 and biased for class AB operation. By using the Curtice nonlinear model [16], [17], we have obtained the optimum load impedance value of T_1, which gives the maximum output power. Then, the elements (the inductance $L_i = 1$ nH and the capacitance $C_i = 0.75$ pF) of the two-port network QAI [see Figs. 1 and 4(a)] have been calculated so that the transistor T_1 is terminated by its optimum load impedance. In this case, the output power at port 2 of the QCM is 20 dBm at a 1-dB compression point.

V. Measurement Results and Comments

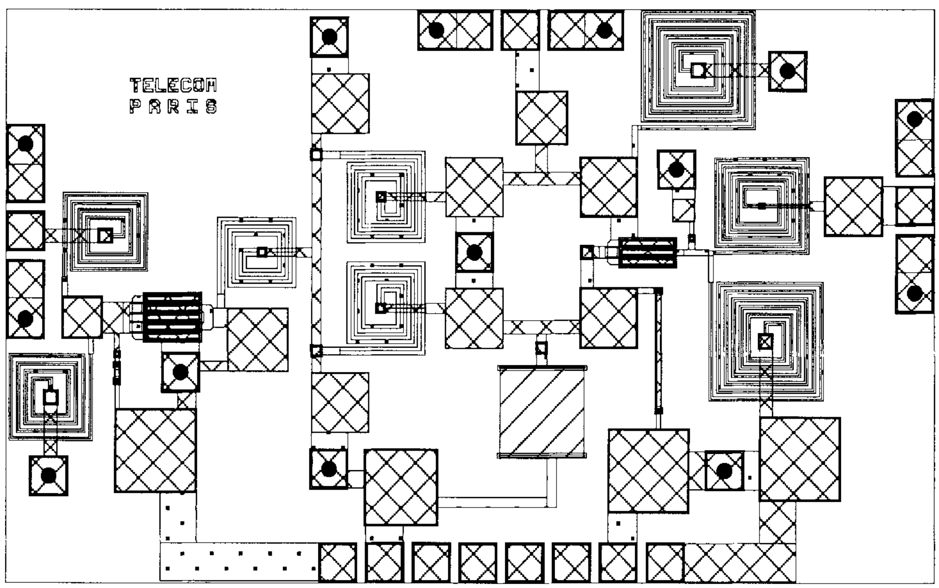
The schematic diagram of the QCM and its layout drawing are shown in Fig. 4. The circuit was made by GMMT foundry, its overall size is about 5 mm^2. The input matching network QAE is realized by two inductances L_{a1} and L'_{a1}. The values of these two elements have been calculated to transform the gate impedance of the transistor T_1 to the 50-Ω impedance. Similarly, the inductance L_{a3} and the capacitor C_{a3} constituting the output matching network QAS are determined to match the output of the transistor T_2. Both 90° phase shifters are realized with lumped elements, i.e., two capacitors C_d and one inductance L_d. The values of these components are calculated at the frequency of 4 GHz. Port 2 of the QCM is matched thanks to the low input impedance presented by

[1] Circuit simulator software available from EESOf, Hewlett-Packard, Palo Alto, CA.



La1 = 3 nH	Ld = 2 nH	Lp2 = 8.5 nH
L'a1 = 3.5 nH	Cd = 0.8 pF	Ca3 = 0.14 pF
C1 = 7 pF	C2 = 12 pF	La3 = 5.5 nH
R1 = 1 KΩ	C3 = 15 pF	Vgs1 = -1 V
CB = 25 pF	Zc = 50 Ω	Vdd1 = 12 V
Ci = 0.75 pF	Lp1 = 8.5 nH	Vgs2 = -1.1 V
Li = 1 nH	R2 = 9 KΩ	Vdd2 = 5 V

(a)



(b)

Fig. 4. (a) Schematic diagram of the quasi-circulator module. (b) Layout of the quasi-circulator module.

the source of the transistor T_2. The gate of T_1 is biased at $V_{\rm gs1} = -1$ V through the resistance R_1 and the gate of T_2 is biased at $V_{\rm gs2} = -1.1$ V through the resistance R_2. Source and drain of T_2 are connected to the RF choke inductors $L_{\rm p1}$ and $L_{\rm p2}$. Voltage of the drain T_2 is $V_{dd2} = 5$ V. The drain of the transistor T_1 is biased through the resistance Z_c with $V_{\rm dd1} = 12$ V. The other components are the dc blocks capacitors (C_1, C_2, and C_3) and the bypass capacitors (C_B). Fig. 5 shows the simulated and the measured results of QCM. For a frequency of 4 GHz, the circuit simulation shows a gain S_{21} of 7.55 dB, a gain S_{32} of 5 dB, a return loss greater than 25 dB, and isolation better than 13 dB. The solid lines in Fig. 5 show the measured values. In this case, the circuit presents gain values of 7.6 and 4 dB between the transmitter–antenna ports and the antenna–receiver ports, respectively, and an isolation S_{31} of 22 dB in the transmit–receive path. The value of this isolation (S_{31}) is different to the value of 35 dB obtained by simulation. The reason of this degradation can be due to the sensitivity of the shunt impedance Z_c. The minimum isolation of 13 dB in the receiver–antenna path is, in most cases, sufficient because the receiver is generally well matched. It can be noticed that the best return losses are obtained at 4.1 GHz instead of 4 GHz and are greater than 14 dB. This small frequency shift can be due to the coupling between elements, which was not taken into account during the simulation. The dc power consumption of the QCM is 0.65 W. Fig. 6 shows the input–output power characteristics of the fabricated quasi-circulator. The circuit presents 18-dBm output power at 1-dB compression point. The IP3 is obtained by applying two signals with the same magnitude at port 1 of the QCM. These two

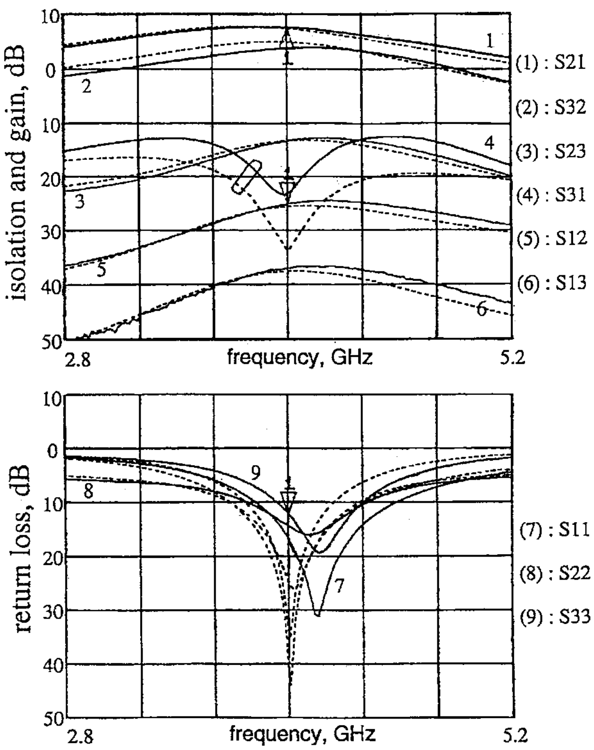


Fig. 5. Predicted (— — —) and measured (——) frequency characteristics of quasi-circulator.

signals have frequencies of $f_1 = 4$ and $f_2 = 4.005$ GHz. Port 3 of the QCM is terminated by a 50-Ω impedance. Using a spectrum analyzer at port 2 of the QCM, we have measured output powers $P_{2f1\text{-}f2}$ and P_{f1} equal to −28.8 and 7.5 dBm for an input power at $f1$ (or $f2$) equal to 0 dBm. By taking into account that the slopes of $P_{2f1\text{-}f2}$ and P_{f1} are 3:1 and 1:1, respectively [15], we have obtained that the IP3 is equal to 25.6 dBm. The measured noise figure values F_{23} between port 2 and port 3 at different frequencies are shown in Fig. 3. We note that the noise figure increases with increased frequency. This variation is similar to the simulation results shown in the same figure. Even the absolute values of the measured and the predicted results agree, with a maximum deviation of 0.3 dB. This noise figure was obtained using 50-Ω source and load impedances.

Finally, it is important to note that this circuit can handle very high power between ports 1 and 2 by simply increasing the width of the transistor T_1. The noise figure F_{23} will always have the same value because it is independent of the noise generated by T_1.

VI. Conclusion

This paper has proven the design for a quasi-circulator module allowing the simultaneous transportation of a medium power signal from transmitter to antenna, and a low-power signal from antenna to receiver. The device demonstrates a noise figure of 5.5 dB and an output power of 18 dBm with associated gains of 4 and 7.6 dB for the receive and transmit paths, respectively. This circuit can be used to transmit very high power by increasing the width of the divider transistor T_1.

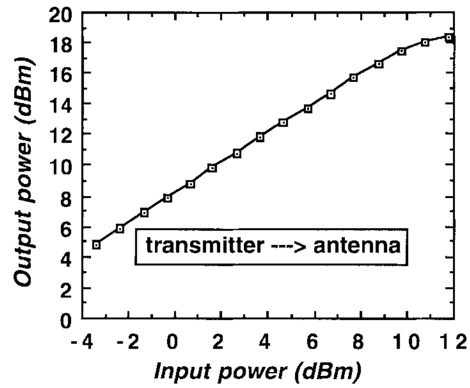


Fig. 6. Power-handling characteristics of the quasi-circulator.

As shown in Section III, the noise figure between ports 2 and 3 of the quasi-circulator can be reduced by 1.27 dB using an active termination instead of the shunt impedance Z_c, which is at room temperature ($T_a = 300°\text{K}$).

Finally, the characteristics of the QCM concerning the power capability and the noise figure can be improved using HEMT technology with appropriate transistors T_1 and T_2.

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