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A Distinctive Method of Eliminating Out-Band Instability in Cascaded Active Device System Based on Narrow-band Attenuation

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Abstract—A distinctive connection method in cascaded RF/MW active device system achieving both stability and low gain loss is presented. Unlike traditional methods (isolator and attenuator), the proposed solution introduces an appropriate length of transmission line to change the input impedance at the out-band instable frequency point and uses a narrow-band termination to absorb the instable power without deteriorating in-band signal. Moreover, the reason that instability often occurs in the cascaded system is analysed with S-parameters, and it turns out to be a kind of out-band instability. The solution is verified by an adjustable circuit example whose insertion loss is below 0.3 dB.

1. INTRODUCTION

RF/MW active devices (such as LNA, Mixer, PA) are widely used in modern communication system. The stability is one of the key aspects in their design [1–4]. It is well known that out-band instability may change the working state of the active device (force it into saturation or even destroy it) and deteriorate the in-band signal. But due to the uncontrollable out-band factors, even if all active devices are measured stable separately, their connection system may be still instable.

The traditional solutions of improving the out-band stability are mainly inserting an isolator, attenuator or a resistor, but sometimes these methods have several limitations [5–7]. For example, if the instable frequency point is far from the in-band, inserting an isolator will not improve the out-band stability because of isolator's narrow band. Due to the wide band of attenuators or resistors, using them can improve the out-band stability. But it will be at the expense of the overall gain and thus result in several other disadvantages. For example in a small signal amplifier, such as first stage of low noise amplifier, reducing gain means increasing noise [8]. For a large signal amplifier, it will deteriorate P1 dB, as well as ACPR, EVM, IP3, efficiency, etc. [9].

In this paper, the proposed solution is based on absorbing the power of the instable frequency point. With power being absorbed only at the instable point, the in-band will be affected a little, but the out-band instability can be solved. Moreover, the central frequency of the narrow-band absorber can be designed independently, so that the proposed solution is also effective for the far away instable frequency point.

The remainder of this paper is organized as follows. In Section 2, the stability of cascaded system is analysed with S-parameters. In Section 3, the solution and an adjustable circuit example (in-band includes 4.7–4.9 GHz and an out-band self-oscillation occurs at 7.3 GHz which is the worst condition because it is far away from in-band) are presented to solve the contradiction between high gain and stability. In Section 4, the experimental results are presented and also compared with the isolator and attenuator. Section 5 gives the conclusions.

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2. *S*-PARAMETERS ANALYSIS OF CASCADED SYSTEM

Assuming that $|S_{12}|$ is small enough, we can simply take $|S_{11}| < 0\,\text{dB}$ and $|S_{22}| < 0\,\text{dB}$ as the stability proviso [9]. So first of all, cascaded formulae of S-parameters are needed to analyse how each single stage influences the cascaded system. As shown in Fig. 1, the output port of the 1st stage (port 2) connects to the input port of the 2nd stage (port 3). The formulae of cascaded S-parameters are shown in (1).

$$\begin{cases} S'_{11} = S_{11} + \dfrac{S_{12}S_{21}S_{33}}{1 - S_{22}S_{33}} & S'_{12} = \dfrac{S_{12}S_{34}}{1 - S_{22}S_{33}} \\ S'_{21} = \dfrac{S_{21}S_{43}}{1 - S_{22}S_{33}} & S'_{22} = S_{44} + \dfrac{S_{34}S_{43}S_{22}}{1 - S_{22}S_{33}} \end{cases} \tag{1}$$

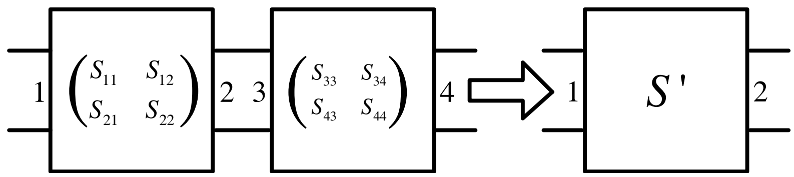

Figure 1. Cascaded system of S-parameters.

Here S'_{11} will be discussed in detail as an example, and the analyses of other S-parameters are similar. For the convenience of presentation, S'_{11} is redefined as (2) in which R_{11} is the second part of S'_{11}.

$$S'_{11} = S_{11} + R_{11} \tag{2}$$

Generally, each stage is well matched in the band so that $|S_{22}|$ and $|S_{33}|$ of the in-band will be good enough, below $-10\,\text{dB}$ for example. Thus, the in-band R_{11} will be approximately equal to zero and S'_{11} will be approximately equal to S_{11}.

But, $|S_{22}|$ and $|S_{33}|$ of the out-band may not be small enough ($-3\,\text{dB}$ for example) so that R_{11} cannot be ignored. In this way, the vector sum (Fig. 2) may be larger or smaller than S_{11} due to the phase of R_{11}. The system may be instable when $|S'_{11}| > 0\,\text{dB}$. In the worst case, we assume that S_{22} and S_{33} are in-phase so that $|R_{11}|$ gets the maximum value. Typical theoretical range of the in-band and out-band S'_{11} is shown in Table 1, and we can see that out-band S'_{11} may exceed 0 dB (instable).

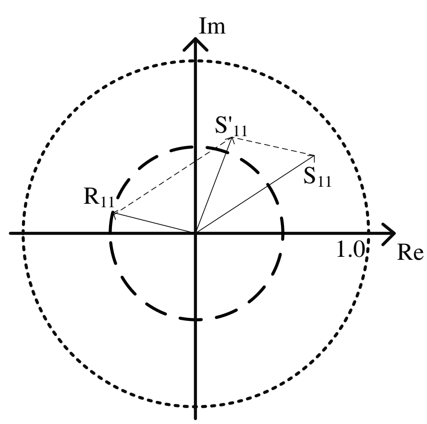

Figure 2. When $|S_{11}|$ and $|R_{11}|$ are constants, the phase of R_{11} determines S'_{11}.

In a word, the second part of S'_{11} is just the main reason that instability often occurs in cascaded system even if all the active devices are measured stable separately. So, only when R_{11} is small enough, does the "true stability" reach ($S'_{11} = S_{11}$).

Table 1. Range of in and out-band S'_{11}.

	S-parameters/dB					
	S_{11}	S_{12}	S_{21}	S_{22}	S_{33}	Range of S'_{11}
In-band	-10	-20	10	-10	-10	$(-14.7, -7.4)$
Out-band	-3	-20	10	-3	-3	$(-11.7, 1.3)$

3. NARROW-BAND ATTENUATION

3.1. Theories of Narrow-Band Attenuation

As shown in Fig. 3, this kind of solution can not only eliminate the out-band instability, but also ensure good in-band signal.

For the in-band signal, the band-pass filter does not work. The transmission line Z_0 only changes the phase of S_{22}. So the in-band S_{21} will not be decreased.

For the out-band signal, Z_{in1} at 7.3 GHz (instable frequency point) can be moved to Z_{in2} (close to the infinite point) via the transmission line Z_0. The added parallel R_f contributes to improving S_{22} of the instable out-band frequency point, as shown in Fig. 4.

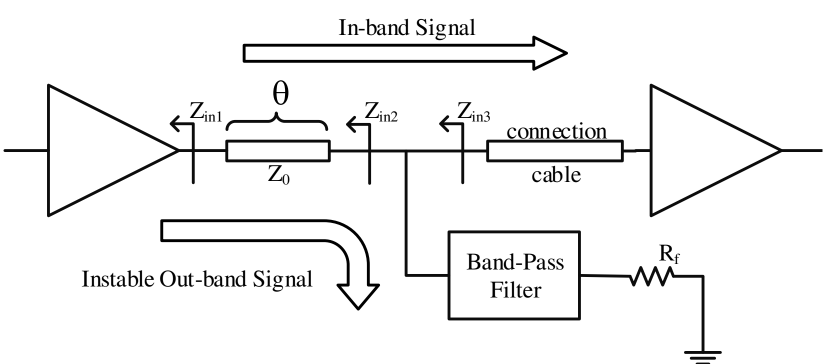

Figure 3. Construct of narrow-band attenuation.

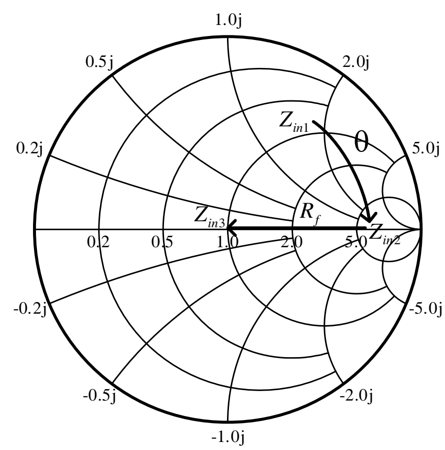

Figure 4. Narrow-band attenuation on smith chart.

3.2. Test Circuit

In order to move Z_{in1} point to Z_{in2} point in experimental process with a suitable θ, we design the test circuit, as shown in Fig. 5. The distance between two branches is 2.7 mm (about 37.5 degrees at 7.3 GHz), and each branch has a $l = 0.25 + n * 0.5$ ($n = 1$ is selected here) wavelength at 7.3 GHz. What we need to do is to use R_f to connect the transmission line Z_0 with one of the branches to get the minimum $|S_{22}|$ at 7.3 GHz.

S-parameters of the transmission line Z_0 (S^t) and the branch including Rf (S^b) are shown in (3). S-parameters of the NBA (S^{nba}) can be solved through (1) and (3), as shown in (4). S-parameters of the 1st stage amplifier and the narrow-band attenuator cascaded system can be solved through (1) and (4), as shown in (5).

$$\begin{cases} S^t_{11} = S^t_{22} = 0 & S^t_{12} = S^t_{21} = e^{-j\theta} \\ S^b_{11} = S^b_{22} = \dfrac{Z_0}{2Z_b j\cot(l) - 2R_f - 2Z_0} & S^b_{12} = S^b_{21} = 1 + S^b_{11} \end{cases} \tag{3}$$

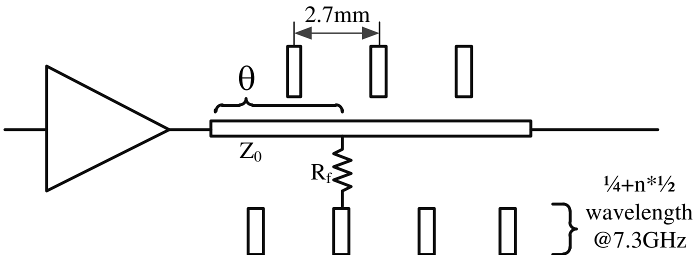

Figure 5. Test circuit.

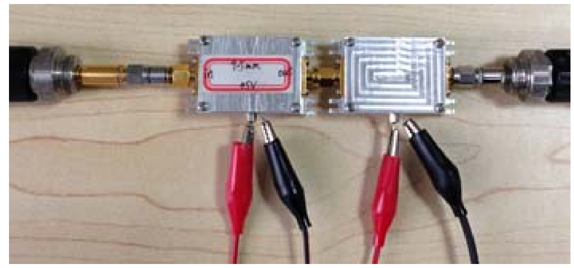

Figure 6. Cascaded system.

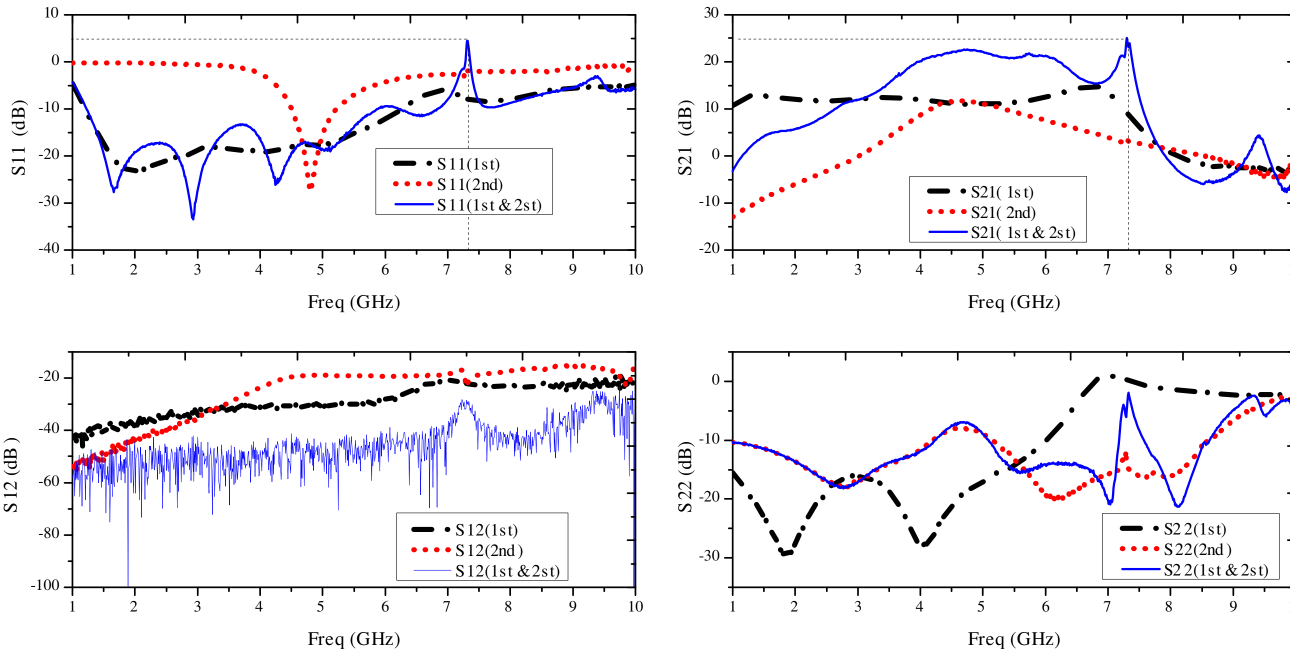

Figure 7. Measured S-parameters of 1st amplifier, 2nd amplifier and their cascaded system. In-band signal includes 4.7–4.9 GHz. An out-band self-oscillation occurs at 7.3 GHz.

$$\begin{cases} S_{11}^{nba} = S_{11}^{b} e^{-j2\theta} \\ S_{22}^{nba} = S_{11}^{b} \\ S_{12}^{nba} = S_{21}^{nba} = (1 + S_{11}^{b}) e^{-j2\theta} \end{cases} \tag{4}$$

$$\begin{cases} S_{11}^{1-nba} = S_{11} + \dfrac{S_{12} S_{21} S_{11}^{b} e^{-j2\theta}}{1 - S_{22} S_{11}^{b} e^{-j2\theta}} \\ S_{22}^{1-nba} = S_{11}^{b} + \dfrac{(1 + S_{11}^{b})^2 e^{-j2\theta} S_{22}}{1 - S_{22} S_{11}^{b} e^{-j2\theta}} \\ S_{12}^{1-nba} = \dfrac{S_{12} (1 + S_{11}^{b}) e^{-j\theta}}{1 - S_{22} S_{11}^{b} e^{-j2\theta}} \\ S_{21}^{1-nba} = \dfrac{S_{21} (1 + S_{11}^{b}) e^{-j\theta}}{1 - S_{22} S_{11}^{b} e^{-j2\theta}} \end{cases} \tag{5}$$

In the 1st stage amplifier and the narrow-band attenuator cascaded system, if $Z_{in3} = Z_0$, the parallel value $Z_{in2}//R_f$ must be Z_0. So we get Z_{in2} and $|S_{22}|$ of the 1st stage amplifier:

$$Z_{in2} = \frac{R_f Z_0}{R_f - Z_0} \tag{6}$$

$$|S_{22}| = \frac{Z_{in2} - Z_0}{Z_{in2} + Z_0} = \frac{Z_0}{2R_f - Z_0} \tag{7}$$

Because Z_{in1} can be moved to Z_{in2} with an electric length of θ, we get:

$$S_{22} = \frac{Z_0}{2R_f - Z_0} e^{j2\theta} \tag{8}$$

For the instable frequency point (7.3 GHz), $l = 1.5\pi$. For the in-band (4.7–4.9 GHz), $l \approx \pi$. Using (3) and (8), (5) can be solved as (9) and (10), where (9) is the S-parameters of the instable frequency point and (10) the S-parameters of the in-band. It can be easily found that the instable frequency point is greatly improved and the in-band almost unchanged.

$$\begin{cases} S_{11}^{1-nba} = S_{11} - S_{12}S_{21}e^{-j2\theta}\dfrac{2R_f Z_0 - Z_0^2}{4R_f^2} \approx S_{11} \\ S_{22}^{1-nba} = 0 \\ S_{12}^{1-nba} = \dfrac{S_{12}e^{-j\theta}(2R_f - Z_0)}{2R_f}, \quad \left|S_{12}^{1-nba}\right| < |S_{12}| \\ S_{21}^{1-nba} = \dfrac{S_{21}e^{-j\theta}(2R_f - Z_0)}{2R_f}, \quad \left|S_{21}^{1-nba}\right| < |S_{21}| \end{cases} \tag{9}$$

$$\begin{cases} S_{11}^{1-nba} \approx S_{11} \\ S_{22}^{1-nba} \approx |S_{22}|\, e^{j0} \\ S_{12}^{1-nba} \approx S_{12}e^{-j\theta(f/7.3),\, 4.7\le f\le 4.9\,\text{GHz}} \\ S_{21}^{1-nba} \approx S_{21}e^{-j\theta(f/7.3),\, 4.7\le f\le 4.9\,\text{GHz}} \end{cases} \tag{10}$$

4. EXPERIMENTAL MEASUREMENTS

4.1. Original Cascaded Amplifier

Here are the measured S-parameters of the 1st stage amplifier, the 2nd stage amplifier and their cascaded system (Fig. 6 & Fig. 7). In-band signal includes 4.7–4.9 GHz. It is easy to find that S_{11} of the cascaded system exceeds 0 dB at 7.3 GHz, and this may come to instability.

4.2. Cascaded Amplifier with Narrow-band Attenuation

Figures 8 and 9 show the experimental results. S'_{11} at 7.3 GHz is improved, and in-band S'_{21} (4.7–4.9 GHz) only decreases by 0.3 dB (including insertion loss of SMA and the long transmission line). Additionally, traditional solutions (isolator & 3 dB attenuator) are also shown in Fig. 10 for comparison. Obviously, the instability still exists in isolator solution, and the gain considerably decreases in attenuator solution.

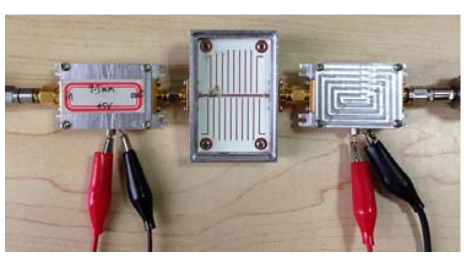

Figure 8. Cascaded system with narrow-band attenuation.

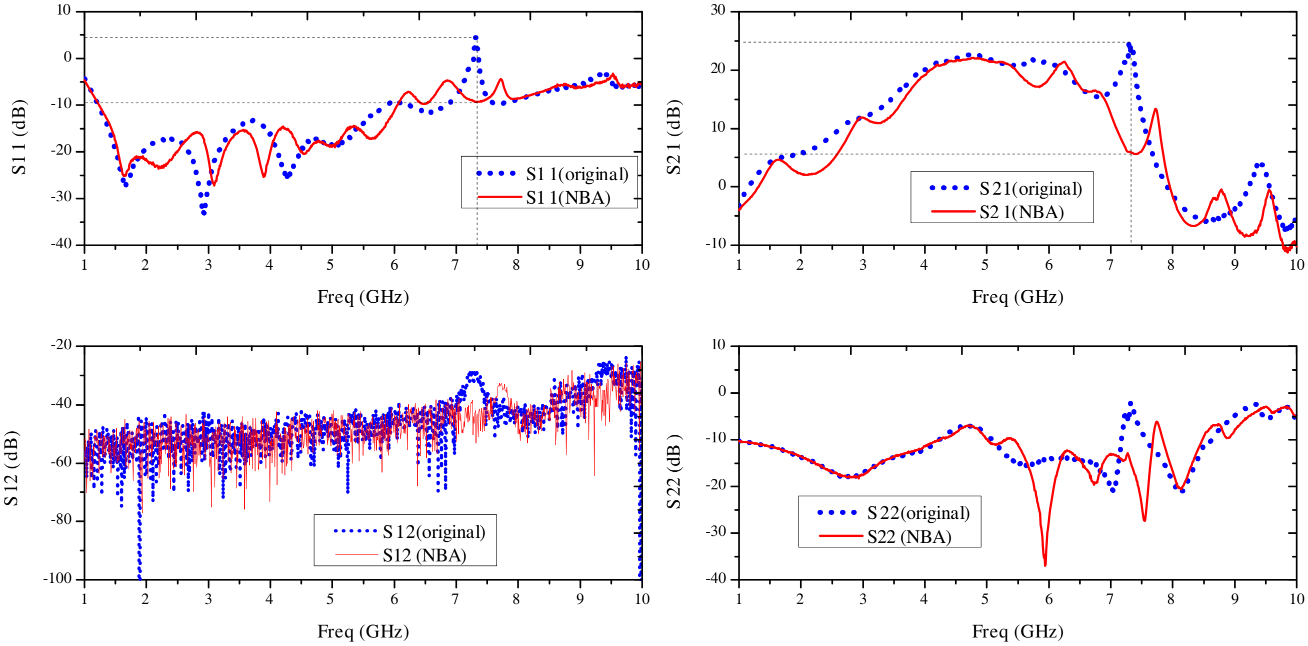

Figure 9. Experimental results with narrow-band attenuation (NBA).

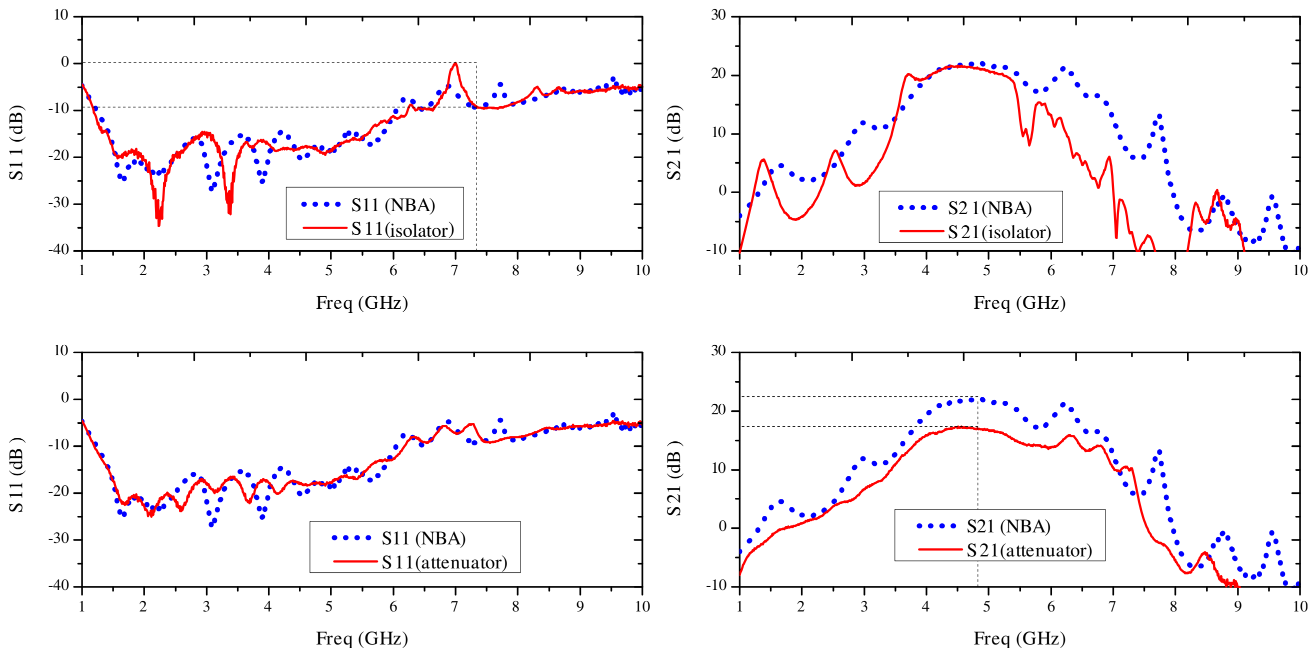

Figure 10. Narrow-band attenuation (NBA) versus traditional solutions (isolator and attenuator).

5. CONCLUSIONS

We have discussed the main reason of the instability in cascaded amplifier system and presented a new solution based on narrow-band attenuation which has concise circuit construct and flexible adjustability. It takes aim at the instable frequency point and can solve the contradiction between high gain and out-band stability very well.

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