Tuning a Bandpass Filter by Optical Control of a Negative-Resistance Circuit

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***Abstract*—A novel tunable active bandpass filter is presented in X-band. Basically, this is an end-coupled half-wavelength microstrip bandpass filter coupled by a high-Q value negative-resistance circuit, which is optically tunable. In this filter, one MESFET works both as a tuning element and negative resistance. To increase the tunability of the active MESFET circuit compared with the half-wavelength resonator, the port of the negative resistance is connected to the open stub through one side line in the quarter-wavelength coupler. Tuning range of 123 MHz is achieved by optical tuning. This optically tunable range of the active bandpass filter exceeds 1% of the center frequency.**

***Index Terms*—Active filter, negative resistance, optical tuning, S-parameter.**

I. Introduction

TUNABLE filters have a wide application in communication systems, and various kinds of tunable filters have been proposed. The yttrium–iron–garnet (YIG) sphere is usually used in a tunable filter, but its tuning speed is slow. A varactor diode can be used in a filter for high-speed tuning. On the other hand, an active filter is suitable for increasing the Q value of the filter. Chang and Itoh proposed the coupled negative-resistance method in an end-coupled bandpass filter for this purpose [1], [2].

The Schottky contact in a MESFET forms a depletion layer and works as a variable capacitance under the reverse bias. Therefore, the MESFET device is also able to be used for filter tuning. If the depletion region of the MESFET with its cover removed is irradiated by a semiconductor laser, electron–hole pairs are created in the depletion layer, and the size of the depletion layer is effectively decreased. Consequently, the active bandpass filter, which uses the gate–source capacitance of a MESFET instead of a varactor diode, can be tuned not only by the gate–source voltage, but also by the light intensity. Based on this concept, an optically tunable active bandpass filter was developed by one of the authors [3]–[5]. We can call this type of filter a "two-terminal MESFET filter."

The MESFET can also be used as a three-terminal varactor by employing all three of the variable capacitances ($C_{\rm gs}$, $C_{\rm gd}$, and $C_{\rm ds}$), which are between two of the three electrodes (drain, gate, and source). Lin and Itoh tried to use one MESFET circuit in the active mode to generate both a negative resistance and a variable reactance. However, the tuning circuit including the MESFET negative-resistance circuit was originally designed for wide-band use [2]. Therefore, tuning using the negative-resistance circuit is not easy, particularly in optical tuning [6]. This type of filter can be called a "three-terminal MESFET filter."

In this paper, it is noticed that the reactance of the negative-resistance circuit can be changed steeply from a negative value to a positive value depending on the frequency in the X-band [2]. If the reactance can also be changed by laser irradiation, it is possible to use the negative-resistance circuit for optical tuning. In Section II, the optical tunability using the input reactances of the MESFET negative-resistance circuit is shown. The following sections report on the principle and available technique of using the MESFET in the negative-resistance circuit for tuning, especially for optical tuning. Experimental results are also given.

II. Optical Control of S_{22} for a MESFET

In a real circuit, the negative resistance is realized by a circuit looking into the drain of the MESFET and including feedback networks. Therefore, the imaginary part of the impedance corresponding to the S_{22}-parameter for the MESFET is important for using the circuit not only for amplifying, but also for tuning.

Fig. 1 shows the S_{22}-parameters for an NE72084B type MESFET (NEC) measured by a Type-360 network analyzer (Wiltron), when the drain voltage (V_d) is 3.0 V and its current (I_d) is 10.0 mA. The curve marked by $\square$ and the one marked by $+$ show the S_{22}-parameters with and without laser irradiation, respectively. The semiconductor laser is an SDL-5311-G1 (SDL) whose wavelength is 827 nm and output power (P_L) is 47 mW. Using a small lens, the light is focused on the gate–source gap area of the MESFET with its cover removed.

As shown in Fig. 1, the S_{22}-parameters can be widely changed by laser irradiation. We have measured other S-parameters, S_{11}, S_{12}, and S_{21}, but they are not shown here because, on the contrary, the other S-parameters are not changed much by the laser irradiation. The input reactances looking into the drain of the MESFET are shown in Fig. 2, which are calculated from Fig. 1, and similar results were obtained when V_d was 3 V and I_d was 30 mA. It can be observed from Fig. 2 that the imaginary components of the input impedances are remarkably changed by the laser irradiation. A novel optical-tuning circuit can be constructed

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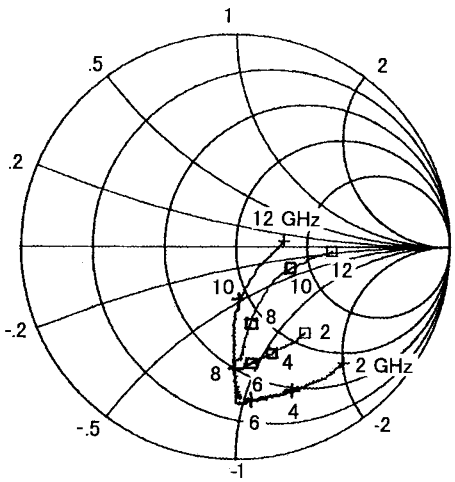

Fig. 1. Measured scattering parameters S_{22} normalized by 50 Ω versus frequency (gigahertz) of an NE72084B- or 2SK571-type MESFET (NEC). The curve marked by □ and the one marked by + show the S_{22}-parameters with and without laser irradiation, respectively. The drain voltage and drain current are 3.0 V and 10.0 mA without laser irradiation. When the gate region is irradiated by the laser, they change to 1.85 V and 37.6 mA, respectively. The laser power is 47 mW and its wavelength is 827 nm.

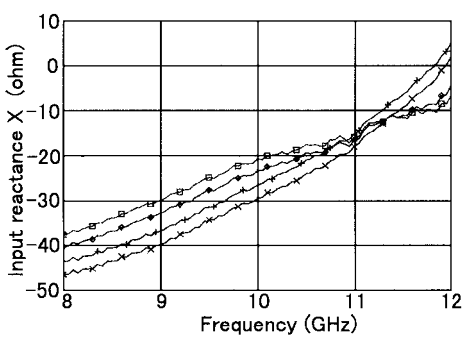

Fig. 2. Measured input reactances X looking into the drain of the MESFET (NE72084B) versus frequency. The curves marked by □ and + show the reactances when $I_d = 10$ mA. The curves marked by ◊ and × show the reactances when $I_d = 30$ mA. The curves marked by □ and ◊ show the reactances when the laser irradiation power is 47 mW. The curves marked by + and × show the reactances without laser irradiation.

using this optically controllable reactance of the MESFET, which also works as a negative resistance.

III. Filter Design Concept

The basic structure of the bandpass filter whose losses are compensated for by a negative-resistance circuit is shown in Fig. 3. This is an end-coupled microstrip bandpass filter, and half of the half-wavelength resonator is modified by a coupling circuit. Unlike the filter originated by Chang and Itoh [1], [2], an open stub is used instead of the matched load connected with the negative-resistance circuit through the coupling circuit, and the half-wavelength resonator is not divided up. Therefore, the half-wavelength resonator shows a fixed resonant frequency. On the other hand, a combination of the negative-resistance circuit, quarter-wavelength coupler, and open stub composes another resonator, and its resonant frequency can be changed by the negative-resistance circuit parameters. The second resonator shows a higher Q value than the half-wavelength resonator because of the negative-resistance circuit. We can call this type of filter a "three-terminal MESFET filter with an open stub."

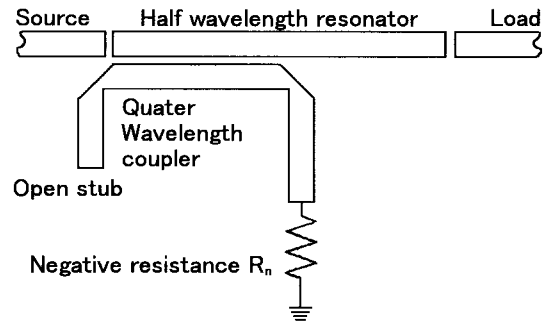

Fig. 3. The basic structure of a one-pole three-terminal MESFET filter with an open stub.

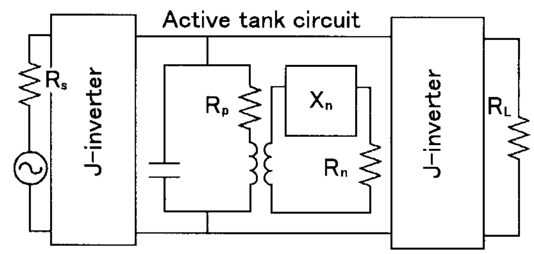

Fig. 4. The equivalent circuit of a one-pole three-terminal MESFET filter with an open stub. The tank circuit loss is equivalent to a dissipating resistor R_P. The resistance and reactance of the negative-resistance circuit are represented by R_n and X_n, respectively.

The equivalent circuit of the filter may be represented by Fig. 4. All of the losses in the tank circuit such as the conductor loss, dielectric loss, and radiation loss can be included in a dissipating resistor (R_p). The quarter-wavelength coupler couples the negative resistance (R_n) to the tank circuit. If circuit parameters are appropriately adjusted, the dissipating resistor (R_p) can be canceled out by the coupled negative resistance (R_n) and a lossless tank circuit may be obtained. On the other hand, the reactance components (X_n) included in the negative-resistance circuit can be controlled by the optical irradiation, as shown in Fig. 2. Therefore, the whole circuit is a double-tuned filter, and its tuning response depends mainly on the high-Q negative-resistance circuit.

IV. Filter Structure and Experimental Procedure

Fig. 5 shows the structure of the one-pole three-terminal MESFET filter with an open stub. The filter is designed with a characteristic impedance of 82 Ω. The input and output of the filter are transformed to the characteristic impedance of 50 Ω by tapered microstrip lines. The MESFET for both tuning and amplifying is an NE72084B(NEC) with its cover removed. The gate of the MESFET is connected to the termination (82 Ω) through a low-pass filter whose cutoff frequency is 8.8 GHz. The low-pass filter makes the MESFET produce a negative resistance at a frequency higher than the cutoff frequency. This circuit was fabricated on a woven-glass-reinforced Teflon substrate with a thickness of 0.76 mm and a dielectric constant

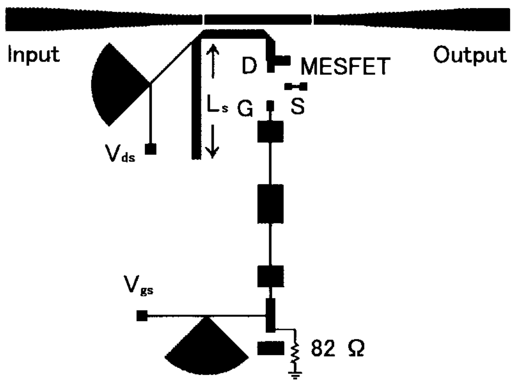

Fig. 5. Circuit pattern of the one-pole three-terminal MESFET filter with an open stub.

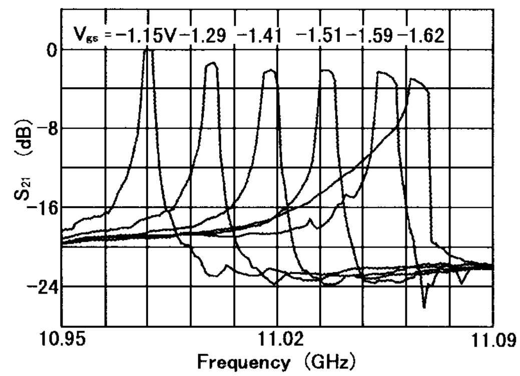

Fig. 6. Frequency shift of the passband as function of the gate–source voltage ($V_{\rm gs}$), $V_{\rm ds} = 1.46$ V, $L_s = 9.6$ mm, and the irradiated laser power (P_L) is 0.

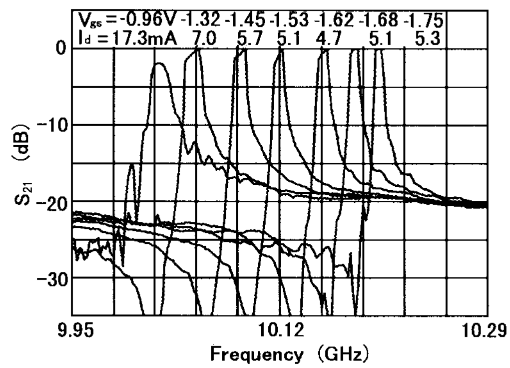

Fig. 7. Frequency shift of the passband as a function of the gate–source voltage ($V_{\rm gs}$) and the drain current (I_d), which also depends on the drain–source voltage ($V_{\rm ds}$), $L_s = 3.6$ mm and $P_L = 0$.

of 2.55. By changing their open-stub lengths (L_s), several kinds of filters were made and their tunable ranges were observed.

The S_{21}-parameters of the filters were measured by a Type-360 vector network analyzer (Wiltron) with and without laser irradiation. The light source was a semiconductor laser [LT015MD0 (Sharp)] whose wavelength was 830 nm. Using a small lens, the light was focused on the gate–source gap area of the MESFET with its cover removed. The output of the laser for irradiation was changed from 0 to 40 mW.

V. Results and Discussion

A. Voltage Tuning

Fig. 6 shows that the frequency shift of the passband depends on the gate–source voltage ($V_{\rm gs}$) of the MESFET without laser irradiation. The length (L_s) of the open stub is 9.6 mm. The parameters of the MESFET are: the drain–source voltage ($V_{\rm ds}$) is 1.46 V, and the drain current (I_d) is changed from 1.60 to 15.56 mA depending on the gate–source voltage ($V_{\rm gs}$). The maximum center frequency is 11.065 GHz and the minimum is 10.976 GHz under the condition that the transmission loss is no more than 3 dB, when $V_{\rm gs}$ is -1.62 and -1.15 V, respectively. The center frequency of the passband is shifted by 89 MHz with the change of $V_{\rm gs}$. The difference between the maximum and minimum center frequencies of the passband at the same open-stub length is deemed the tuning range. Therefore, in this case, the voltage tuning range is 86.4 MHz. The 3-dB bandwidths are between 3.8 and 7.6 MHz.

In Fig. 2, the optical changes of the reactance are shown by the shifts from $+$ to $\Box$ and from $\times$ to $\Diamond$. On the other hand, the shifts from $+$ to $\times$ show the reactance changes due to the drain current change. The optical changes are noticeable compared with the changes due to the drain current shift. The drain–source voltage is constant in the experimental conditions, so the drain current is controlled just by the gate–source voltage. The optical change of the reactance is greater than the change due to the variation in the gate voltage. Therefore, the optical tuning is more available than the gate voltage tuning. To substantiate the above remarks, the tuning ability due to both the gate–source and the drain–source voltages were also observed and are described below.

Fig. 7 shows that the frequency shift of the passband depends on both the drain–source voltage ($V_{\rm ds}$) and the gate–source voltage ($V_{\rm gs}$) of the MESFET without laser irradiation. The length (L_s) of the open stub is 3.6 mm. The drain current (I_d) is changed from 5.24 to 17.26 mA depending on both $V_{\rm ds}$ and $V_{\rm gs}$. The maximum center frequency is 10.200 GHz and the minimum is 10.019 GHz. Therefore, the tuning range of 181 MHz is obtained.

B. Optical Tuning

Fig. 8 shows that the frequency shift of the passband depends on the laser irradiation power. The open-stub length (L_s) is 1.1 mm. The parameters of the MESFET are: $V_{\rm ds}$ is 1.23 V, $V_{\rm gs}$ is -1.87 V, and I_d is changed from 0.02 to 17.61 mA depending on the laser irradiation power. The maximum center frequency is 10.789 GHz and the minimum is 10.675 GHz, when the laser power is 0 and 40 mW, respectively. Therefore, the tuning range of 114 MHz is obtained. On the other hand, we can see from Fig. 8 that the shift of the passband center frequency is not proportional to the irradiated laser power. Only 1 mW of the laser irradiation occurs for the center frequency shift of 74 MHz. This frequency shift is almost twice as much as the shift due to the 1-mW laser irradiation in the two-terminal MESFET filter [5].

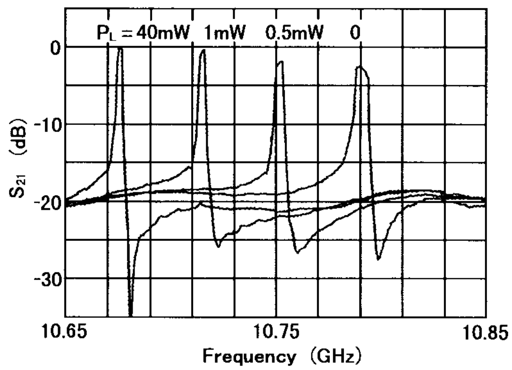

Fig. 8. Frequency shift of the passband as function of the irradiated laser power (P_L), $L_s = 1.1$ mm, $V_{\rm gs} = -1.87$ V, and $V_{\rm ds} = 1.23$ V.

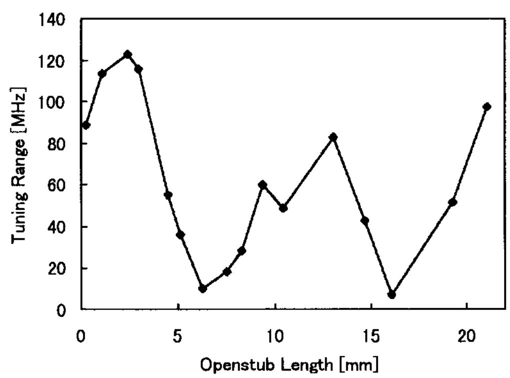

Fig. 9. Optical-tuning region with the irradiated laser power (P_L) as function of the open-stub length L_s. Depending on L_s, the drain voltage ($V_{\rm ds}$) is changed from 1.00 to 1.68 V, and $V_{\rm gs}$ is changed from 1.10 to 1.72 V, respectively. The drain current (I_d) is changed from 4.99 to 29.82 mA depending on P_L.

C. Maximum Tuning Range

Fig. 9 shows the optical tuning ranges by changing laser power between 0–40 mW as a function of the open-stub length (L_s). In this figure, it can be observed that the tuning ranges change periodically. The open-stub length interval between successive repetitions of the peak tuning ranges is almost equal to the half-wavelength because the whole circuit is a double-tuned filter. The maximum tuning range of 123 MHz is obtained when the open-stub length is 2.38 mm. This optically tunable range is notably increased compared with the results for both the two-terminal MESFET filter [7] and the three-terminal MESFET filter [6]. Furthermore, it exceeds 1% of the center frequency (10.48 GHz) of the passband. This improvement in the filter tunability is fulfilled by the use of the open stub instead of the matched load of the three-terminal MESFET filter.

VI. Conclusions

A novel laser-controlled active bandpass filter in X-band was presented. One MESFET provides both a negative resistance and tuning element. To increase the tunability of the negative-resistance circuit, the port of the negative-resistance circuit is connected to the open stub through one side line in the quarter-wavelength coupler. A noticeable shift of the passband center frequency (123 MHz) is observed by the irradiation of the MESFET by a laser (830 nm, 40 mW). This optically tunable range of the active bandpass filter exceeds 1% of the center frequency and exceeds the results of the two-terminal MESFET filter and the three-terminal MESFET filter.

These improvements in optical tunability and the simplified circuit configuration are realized by the use of the open-stub terminated negative-resistance circuit.

Although the results presented here are preliminary, they indicate the possibilities of fabricating an optically tunable active bandpass filter using one MESFET both as a variable reactance and a negative resistance.

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