Temperature Compensated Planar Narrow-band Notch Filter with Fully Automated Laser-Trimming

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***Abstract* — A new narrow-band notch filter using a planar dual mode ring resonator (RR) is presented. The resonator operates at harmonic frequencies and is manufactured on a temperature stable calcium magnesium titanate substrate, using photo-lithographic thinfilm processes. An innovative fully automated active laser-trimming procedure is used to adjust the center frequency and the bandwidth of the filter.**

High unloaded quality factors of more than 400 have been obtained at Ka-band frequencies. With these high quality factors a 3dB-bandwidth of less than 1% in conjunction with a notch depth of more than 40dB can be achieved. In addition, the frequency tuning range of the laser-trimming is larger than 10% without any significant change of the filter characteristic or the quality factor of the resonator. The measured temperature coefficient of the filter is –2ppm/K.

We use a notch filter with an electrical length of four wavelengths to suppress the undesired residual local oscillator signal in the transmitter chain of our latest microwave Point-to-Point (PP) and Point-to-Multipoint (PMP) transceivers.

I. Introduction

Demand of wireless communication systems has been growing rapidly during the last years and today new frequency bands have to be opened. Moreover, very wide band frequency ranges are required for high-speed data communication. Ka-band and millimeter-wave frequency ranges are applicable for nowadays and future data communication systems, such as Point-to-Point (PP), Point-to-Multipoint (PMP) and satellite communication systems. These systems strongly require smaller and cheaper RF components, but keeping the same level of excellent RF characteristics than years ago. In addition, for high volume production fully automated tuning and testing is necessary.

Dielectric resonators (DR), e.g. laterally coupled to a microstrip line [1,2], are often used for filter applications at microwave frequencies. DR-filters can achieve high quality factors. The tuning of the resonators, especially the adjustment of the center frequency, requires mechanical tuning elements, which have to be integrated into the filter housing. In an RF module using chip & wire technology those tuning elements additionally have to be hermetically sealed. Thus, the filter becomes complex and expensive.

In contrary, filters in microstrip technique can be manufactured at low cost levels. On the other hand their quality factor, compared to the DR-version is low. They have a high temperature drift and they are difficult to trim. However, low temperature drift and accurate trimming (e.g. to compensate for substrate material and production tolerances or to adjust a channel dependent center frequency) is necessary for narrow-band filters. Therefore, commercially applicable narrow-band filters in microstrip technique are very unusual up to now at Ka-band frequencies.

This paper describes a new approach for a Ka-band planar narrow-band notch filter, that eliminates the above identified disadvantages of narrow-band microstrip filters.

II. Resonator and Filter Design

A. Configuration

Fig. 1 shows the basic configuration of the planar notch filter proposed in this paper. A ring resonator (RR) is coupled to an adjacent transmission line.

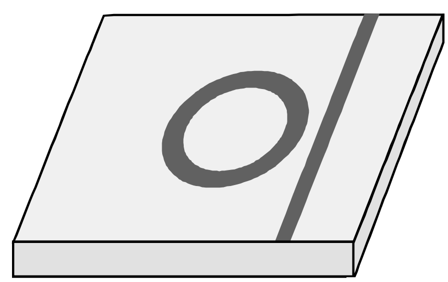

Fig. 1. Basic configuration of the planar notch filter with ring resonator and coupling line, printed onto a substrate.

Due to the symmetrical structure of the RR, there are always two orthogonal modes propagating in the resonator [3,4]. To increase the quality factor of this dual mode resonator a low characteristic impedance of the resonator and an operation at harmonic frequencies instead of the fundamental frequency was chosen. A relative dielectric constant of the substrate of $\varepsilon_r \approx 21$ additionally reduces undesired radiation losses. Due to these operation conditions, ohmic losses as well as radiation losses of the RR are considerably reduced. The result is an increased quality factor of the resonator. Another significant advantage of

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our new approach is that fringing fields, especially like those of DR-filters, and related undesired coupling effects within the transmitter chain of the transceiver are completely eliminated.

B. Resonance Frequency and Unloaded Q

We have used extensive electromagnetic simulations to calculate and optimize the resonance frequency and the quality factor of the RR. In addition, the coupling between the RR and the microstrip line as well as the electrical behavior of the whole notch filter have been investigated. High unloaded quality factors of more than 400 have been obtained at Ka-band frequencies. Agreement between calculation and measurement results is very good.

C. Thermal Stability

A temperature compensated ceramic substrate, based on calcium magnesium titanate with a relative dielectric constant of $\varepsilon_r \approx 21$, is used. Due to the high dielectric constant the electromagnetic field of the resonator is concentrated in the substrate and therefore the influences of the thermal expansion of the housing can be neglected. The temperature coefficient of the resonance frequency τ_f of a RR with an electrical length of four wavelengths is derived from [5] and electromagnetic field analysis as follows

$$\tau_f = \frac{\partial f}{\partial T} \approx -1.04\alpha_{lin} - 0.52\tau_\varepsilon$$

where α_{lin} is the linear thermal expansion coefficient of the substrate and τ_ε is the temperature coefficient of the substrate's dielectric constant. The linear thermal expansion coefficient α_{lin} of the calcium magnesium titanate substrate is approximately 9ppm/K. This means, that for optimum temperature compensation of the resonance frequency a temperature coefficient of the dielectric constant of $\tau_\varepsilon \approx$ -18ppm/K is required.

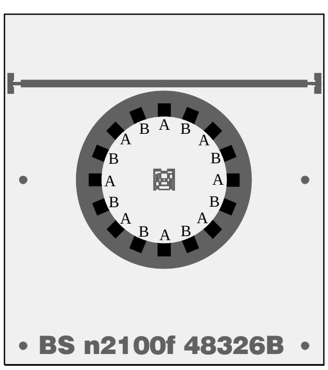

Fig. 2. Layout of a notch filter with an electrical length of four wavelength, including trimming areas of mode A and B.

III. Layout and Fabrication

Fig. 2 shows the layout of a realized notch filter. The marked darker squares at the inner radius of the ring resonator are the potential laser-trimming areas for the both modes A and B. The thickness of the temperature compensated calcium magnesium titanate substrate is 15mil. The filter is manufactured using thin film gold as conductor layer. The applied processes are similar to those used for standard alumina substrates.

IV. Fully Automated Laser-Trimming

A. Laser-Trimming Principles

We use a notch filter with an electrical length of four wavelength to suppress the undesired residual local oscillator signal in the transmitter chain of our latest microwave Point-to-Point (PP) and Point-to-Multipoint (PMP) transceivers. The frequency of the local oscillator signal is channel dependent in our application. Therefore, we have to trim the center frequency of the notch filter for each channel as well. This is done by automated active microwave laser-trimming during the adjustment of the complete transceiver module.

For a proper operation of the notch filter it is necessary to trim both modes of the resonator. During the trimming procedure conducting material of the ring resonator structure is removed by the laser in that way, that the electrical length of the RR increases. Consequently, the resonance frequency decreases.

The maximum tuning effect to the resonance frequency of one mode (A) can be achieved in areas, where this mode has its current maximum. Due to the orthogonality of the two modes, the other mode (B) has its current minimum in this area. Therefore, the tuning effect on this mode is minor and vice versa. The areas with maximum tuning effect to the resonance frequency of mode B are between the areas with maximum tuning effect to the resonance frequency of mode A. The marked darker square areas at the inner radius of the RR, as shown in Fig. 2, are examples of trimming areas of the modes A and B. This realized notch filter has an electrical length of four wavelength.

The resonance frequency of each mode is trimmed separately. This gives us the ability to vary the filter characteristic. We can chose between a single transmission zero or two attenuation poles with tunable frequency offset. Thus, the bandwidth of the notch can be varied.

The trimming process is irreversible. Therefore, especially during fine trimming we have to be careful, that not too much material is removed from the trimming areas by the laser.

B. Implementation and Example

During the trimming procedure the transmission characteristics of the filter have to be determined and evaluated several times. The slopes of the measured characteristics are mainly used to calculate the next trimming step from an initial measurement. The whole trimming procedure is software controlled by a HP-VEE program.

The following figures show measurement results during the trimming of a notch filter. The filter has a startup center frequency of 25.379GHz as shown in Fig. 3 and Fig. 6. The trimming goal is 24.16GHz with a maximum attenuation at this frequency. This means, that both modes have to be trimmed down over more than 1.2GHz to exactly the same frequency.

Fig. 3 shows measurement results during the coarse trimming of the filter. During this procedure it has to be assured, that both modes are separated not too far in frequency. Otherwise the notch depths of the modes decreases to much and the analysis of the measurement results during the fully automated trimming procedure is getting uncertain.

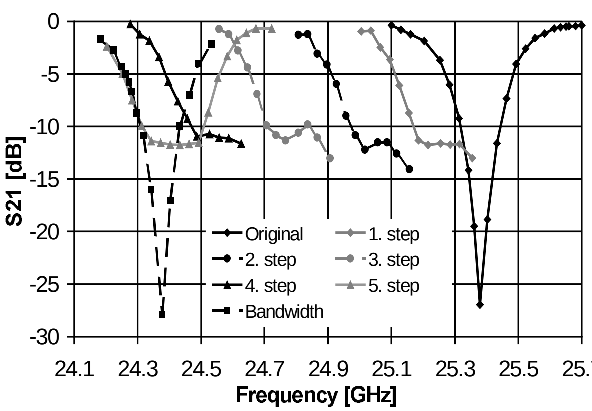

Fig. 3. Measurement results during the coarse trimming of the notch filter.

For a clear correlation between mode and filter slope both modes are separated in frequency approximately 200MHz in a first step (1. step). Afterwards the resonance frequencies of both modes are shifted to lower frequencies simultaneously (2. to 5. step). During this procedure the filter characteristic doesn't change significantly. If the left slope of the filter characteristic is close to the desired center frequency, the bandwidth is corrected (Bandwidth). After that step the filter shows its typical characteristic with a distinctive transmission minimum.

The fine trimming of the notch is slit into two parts. In the first part, the transmission minimum is moved further in the direction of the desired notch frequency. There are several steps necessary to do this (not all of them are shown in Fig. 4).

In the second part (s. Fig. 5) the frequency of the transmission minimum and its distance to the desired center frequency is determined first. Afterwards, the transmission minimum is moved towards the desired center frequency and then minimized at that frequency. Similar to the first part of the fine trimming, there are several steps necessary (not all of them are shown in Fig. 5).

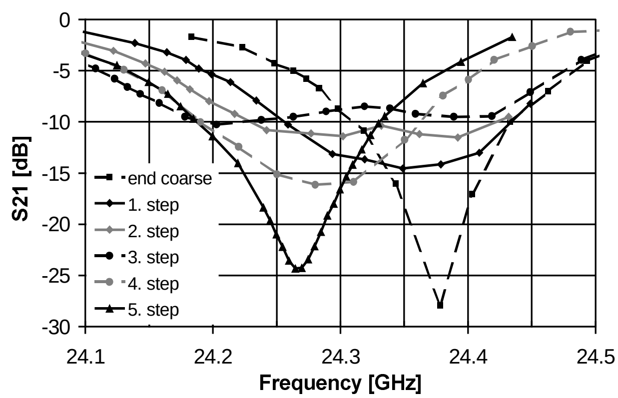

Fig. 4. Measurement results during the fine trimming of the notch filter, first part.

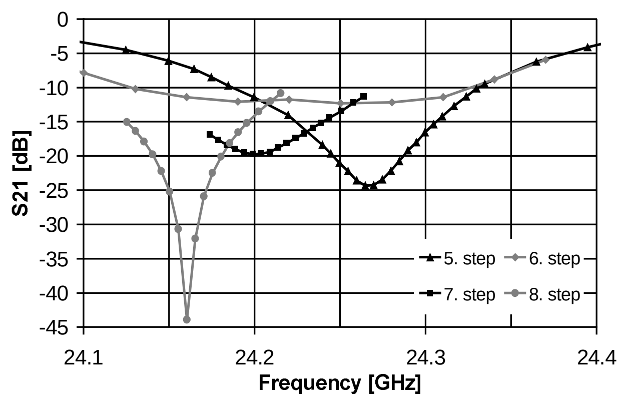

Fig. 5. Measurement results during the fine trimming of the notch filter, second part.

In this example, the frequency of the transmission zero is only 1MHz above the desired center frequency. The notch depth is 43.5dB.

The finally achieved trimming accuracy of the center frequency is better than +/- 0.01%. It is impossible to reach this class of accuracy by use of alternative tuning methods like bond wire trimming or attach of ceramic tuning chips.

V. Measurement Results

The calculated resonance frequency of the filter with an electrical length of four wavelengths and a layout according to Fig. 2 without laser-trimming is 25.40GHz. Fig. 6 shows the measured transmission characteristic of the realized filter. No laser-trimming was applied. The measured resonance frequency is 25.379GHz and the maximum attenuation is 27dB, respectively. The 3dB-bandwith of the filter is only 1.1% and the unloaded Q-factor is 410. For a frequency offset of more than 280MHz from the center frequency the transmission loss is less than 0.5dB.

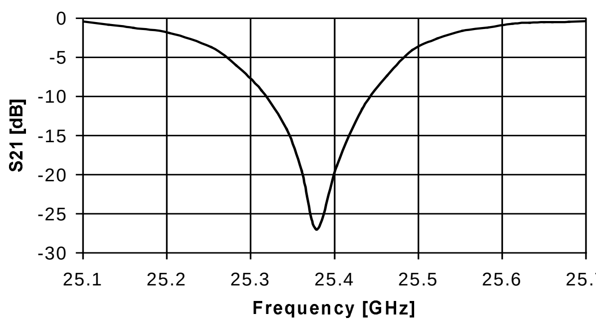

Fig. 6. Measured transmission characteristic without laser-trimming.

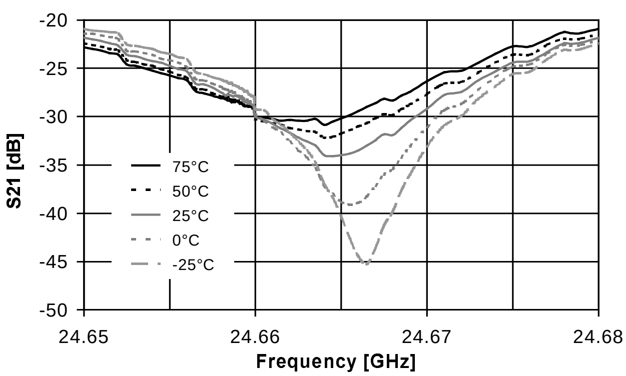

Fig. 7. Measured transmission characteristic of a laser-trimmed filter at several temperatures.

The filter characteristics of a notch filter over temperature are shown in Fig. 7. The center frequency of this filter has been trimmed by the laser to 24.665GHz at room temperature. The achieved notch depth is 34dB. Over a temperature range of 100°C the temperature drift of the notch frequency is less than 5MHz or -2ppm/°C and the suppression at 24.665GHz is better than 30dB over the whole temperature range.

The large variation of the notch depth results primarily from two different mechanisms. First, the quality factor of the filter decreases with increasing temperature and second, the two modes have slightly different temperature coefficients. These measurements have been permormed by using a filter integrated into the transmitter chain of a Point-to-Multipoint (PMP) Ka-band transceiver. The influence of housing and lid on the notch center frequency is less than 1MHz.

VI. Conclusions

In this paper a new approach for a Ka-band planar narrow-band notch filter is presented. Due to the high quality factor of the resonator, a very small bandwidth in combination with a large notch depth is achieved. Therefore, this planar filter can be used now for applications, which have been exclusively reserved up to now for much more expensive filters using dielectric resonators only.

The notch filter has a very low temperature drift and can be manufactured easily using thin film technology. The fully automated active microwave laser-trimming procedure is used to compensate the substrate's material- and production-tolerances and allows finally a flexible adjustment of the center frequency and the desired filter characteristic. Consequently, this filter is suitable for nowadays and future commercial high volume production of microwave transceivers at reasonable cost levels.

Acknowledgement

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