Figure of Merit and Limiting Characteristics of Tunable Ferroelectric Microwave Devices

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Abstract

Microwave application of ferroelectrics is very promising for electrically tunable microwave devices based on the electric field dependence of the dielectric permittivity. Tunable filters and controllable phase shifters are successfully designed as integrated circuits based on multilayer structures containing thin epitaxial ferroelectric (FE) film. As a rule lumped ferroelectric capacitors are used as the tunable components. Quality of the capacitor can be evaluated using Commutation Quality Factor (CQF). There is a unique connection between the Figure of Merit of a tunable microwave device and the CQF of the FE capacitors used. The Figure of Merit gives the upper limit of the quality of a tunable device based on the FE components.

Introduction

Tunable devices are widely used in modern telecommunication systems. Phase shifters, tunable resonators and filters are of the most importance among them. Practical realization of the devices depends mostly on a tunable component used for the device control. Tunable ferroelectric (FE) capacitors are considered as the most suitable choice, when high speed of tuning, simple manufacturing process and low cost are of higher priority [1]. For the tunable capacitor, it is convenient to use the Commutation Quality Factor (CQF) as the main characteristic. There are some different definitions of the CQF, which are based on two main parameters: tunability of the capacitor and the loss factor of the FE material [2]. We suggested the CQF, which is invariant to the parameters of any lossless two-port network connected with the tunable capacitor [3]. This form of the CQF allows estimation of a tunable device quality [4], [5]. The tunable device is described by a set of the most important parameters: pass band width, tuning frequency range, insertion loss for the tunable resonator and filter; phase shift and insertion loss for the phase shifter. The Figure of Merit (FM) as a unified parameter can be used for a comparison of different tunable devices. The FM of a tunable device depends on the CQF of the tunable components and on the quality factor of non-tunable device components. The most significant advantage of the CQF definition used in this work is the possibility to evaluate the upper limit of the FM for a tunable device.

Commutation Quality Factor of a Ferroelectric Capacitor

Equivalent diagram of a ferroelectric capacitor consists of a capacitance and a resistance connected in series. Both the capacitance and the resistance depend on biasing voltage applied to electrodes of the capacitor. A correct model was derived for a description of the dielectric permittivity and loss tangent of a ferroelectric film as a function of a biasing electric field [6], [7]. The capacitor as a tunable component is presented by the two-state equivalent diagram (Fig. 1) with $Z_1 = R_1 + iX_1$ corresponding to zero biasing voltage and $Z_2 = R_2 + iX_2$ obtained under the control voltage $V_b$.

The generalized definition of the CQF for a tunable component [4], [5] is determined by real and imaginary parts of the impedance of the two-state equivalent model:

$$K = \frac{(X_2 - X_1)^2}{R_1 \cdot R_2} + \frac{R_2}{R_1} + \frac{R_1}{R_2}$$ (1)

In the case of FE capacitor, the imaginary part of the component impedance is much higher than the real part. This leads to more simple form of the CQF for the tunable FE capacitor [3], [4]:

$$K = \frac{(n - 1)^2}{n \cdot \tan \delta_1 \cdot \tan \delta_2}$$ (2)
where $n = C_1/C_2$ is the tunability and $\tan \delta = R \cdot \omega C$ is the loss tangent of the capacitor. The CQF decreases when the operating frequency goes up due to loss tangent increasing while the dielectric permittivity of the ferroelectric film does not depend significantly on frequency up to 100 GHz.

**Figure of Merit of a Tunable Resonator**

As it was noted in Introduction, the FM of a tunable microwave device is a measure of the device quality and is determined by the most important device parameters. For a tunable resonator, these parameters are i) tuning frequency band determined as a difference between the lowermost resonant frequency $\omega_{01}$ and the uppermost resonant frequency $\omega_{02}$, ii) the bandwidth of the resonant characteristic $\Delta \omega_{1,2}$, and iii) the quality factor $Q_0 = \sqrt{Q_{01}Q_{02}}$. The FM of the tunable resonator is

$$F = \frac{\omega_{02} - \omega_{01}}{\sqrt{\Delta \omega_1 \cdot \Delta \omega_2}} = (\gamma - 1) \cdot Q_0$$  \hspace{1cm} (3)$$

where $\gamma = \omega_{02}/\omega_{01}$ is the tunability of the resonator. If the quality factor of inductance is much less than the same parameter of the FE capacitor in a series or a parallel tank, the quality factor of the tank is determined by the loss factor of the FE material. In this case Eq. (3) can be written as [8]:

$$F = \frac{1}{2} \sqrt{K}$$ \hspace{1cm} (4)$$

where $K$ is the CQF of the ferroelectric capacitor. The maximum available FM of a tunable resonator depends on the CQF of the capacitor only.

The FM of a resonator based on transmission line sections depends strongly on a coupling coefficient of the capacitor and is lower than (4). A simple realization of microstrip tunable resonators presented in [9] is shown in Fig. 2. The coupling coefficient of the capacitor depends on the electrical length $\Theta_0$ and $\Theta_g$ of transmission line sections. There is a maximum of FM of the tunable resonator for the FE capacitor with given CQF provided by optimal values of $\Theta_0$ and $\Theta_g$.

![Figure 2: Tunable microstrip resonators with ferroelectric capacitor: short-circuited (a) and open-circuited (b).](image-url)
Figure of Merit of a Tunable Filter

The most important parameters of a tunable filter are the same as for a tunable resonator except the quality factor that is less important than in-band insertion loss of the filter in both states $L_{1,2}$ (in dB). Thus the FM of a tunable filter has the following form [8], [9]:

$$F = \frac{\omega_{02} - \omega_{01}}{\sqrt{\Delta \omega_1 \cdot \Delta \omega_2}} \cdot \frac{1}{\sqrt{L_1 \cdot L_2}} \text{[dB}^{-1}]$$

(5)

where $\omega_{01,02}$ are the central frequencies of the filter and $\Delta \omega_{1,2}$ is the filter pass band width at both states. After some transformations [8] one could rewrite (6) in the following form:

$$F = \left( \sqrt{\gamma} - \frac{1}{\sqrt{\gamma}} \right) \cdot \sqrt{\frac{Q_{01} \cdot Q_{02}}{4.34 \cdot N}} \text{[dB}^{-1}]$$

(6)

where $\gamma = \omega_{02}/\omega_{01}$ is the tunability of the filter, $Q_{01,02}$ is the quality factor of the filter resonators at both states and $N$ is the filter order. The maximum FM of a tunable filter is

$$F = \frac{\sqrt{K}}{8.68 \cdot N} \text{[dB}^{-1}]$$

(7)

where $K$ is the CQF of the tunable FE capacitor. Resonators presented in Fig. 2 were used to realize a tunable filter based on ferroelectric capacitors [9]. It was shown in [10] that FM of tunable filter has a maximum depending on the electrical length of the microstrip line sections (coupling coefficient of the FE capacitor).

The 3-pole tunable filter based on sandwich BSTO ferroelectric capacitor [11] with $K = 1600$ at 20 GHz and $K = 256$ at 40 GHz demonstrated $f_{02} - f_{01} = 7.8\text{GHz}$, $\Delta f = 3.9\text{GHz}$, and $\sqrt{L_1 L_2} = 4.5\text{dB}$ at 39 GHz, which gives in line with (5) $F_{\text{exp}} = 0.15 \text{dB}^{-1}$. This value of FM is close to the theoretical limit $F_{\text{max}} = 0.17 \text{dB}^{-1}$ calculated by (7).

Figure of Merit of a Phase Shifter

Phase shifters may work in analog or digital mode of operation. The FM of the phase shifter depends on the phase shift $\Delta \varphi$ and insertion loss $L_{1,2}$ (in dB):

$$F = \frac{\Delta \varphi}{\sqrt{L_1 \cdot L_2}} \text{[deg dB]}$$

(8)

For a phase shifter with FE tunable capacitor and lossless non-tunable components, the FM depends on the CQF of the FE capacitor only and equation (8) turns into [12]:

$$F = m(\Delta \varphi) \cdot \sqrt{K} \text{[deg dB]}$$

(9)

where $m(\Delta \varphi)$ is a coefficient that depends on the phase shift (for example, $m = 6.6$ for $\Delta \varphi = 180^\circ$).

The FM of phase shifters based on FE capacitors with $K = 400 - 1000$ are characterized by $F = 60 - 100\text{deg dB}$ [12,13].

Conclusion

A unified FM of tunable and controllable devices is suggested. The maximum available value of the FM is limited by the CQF of a tunable component. Both the CQF and the FM can be considered as a working tool for optimisation of technology and design of tunable microwave devices.

REFERENCES