Microwave Planar Varactor Tuned Bandpass Filters : Historical Overview

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Abstract

This paper overviews the history of a class of varactor tuned bandpass filters. Since the miniaturization as well as the high performance of the tunable bandpass filters is required for the next generation mobile communication systems, the discussion is focused on the various planar type tunable filters including active configurations. Brief design concepts of various tunable filter configurations as well as their characteristics are discussed.

Ⅰ. Introduction

The next generation mobile communication systems will require reconfigurable RF bandpass filters. Small sized filters which possess high performances including a wide tuning range are generally required. The filters which can fulfill such requirements will be varactor tuned bandpass filters. Traditionally, tunable filters are tuned by adjusting the cavity dimensions of the resonators [1] [3] or altering the resonant frequency of ferromagnetic elements [2] [4-10]. However, these methods are not very useful due to either the large volume or large tuning time. For these reasons, solid-state varactor diodes became popular choices as tuning elements even though new design based MEMS technology has emerged. The varactor tuned bandpass filters can have various configurations such as combline, interdigital, coupled microstrip ring, hairpin and coupled line configurations. Even if there exist slight differences in the design, the standard bandpass filter design scheme is generally applied. Since the Q values of the varactor diodes are low, they are the major source of the insertion loss of the tunable bandpass filters. Therefore, varactor-tuned active bandpass filters have been introduced. These techniques lead the microwave active filters to have low insertion losses and high selectivity. MMIC as well as LTCC technologies has enabled us the miniaturization of active tunable filters. However, the use of active elements in microwave system has also introduced new problems such as stability, noise figure and intermodulation distortion.

In this paper, an attempt has been made to describe the advances in passive and active tunable filters. In section II and III, we will discuss the design schemes as well as the performances of the passive [13-34] and active varactor tunable filters [35-48] realized in various configurations.

II. Design of passive tunable bandpass filters

In this section, the characteristics of the typical passive tunable filters employing ring resonators and combline as well as interdigital configurations will be discussed.

A. The varactor tuned combline filter [13-21]

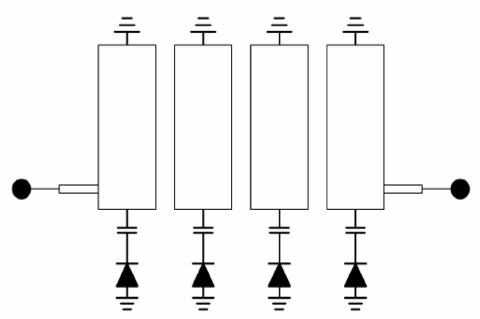


Fig. 1. The typical varactor tuned combline bandpass filter.

Fig. 1. shows a typical varactor tuned combline bandpass filter given in [13]. The resonator consists of multi-microstrip transmission lines shorted at the same ends and loaded with varactor diodes at opposite ends. The transmission must have the electrical length which is less than that of a quarter wavelength line, in order to be resonating with the capacitance of varactor diode at the center frequency of the filter. This configuration can provide a wide tuning range with minimum degradation of the passband performances. A bandpass filter which has more than 0.45 octaves tuning range with less than 12.5 % passband bandwidth variation has been reported [13]. Equivalent circuits of the varactor tuned combline filters and the optimum design methods have been proposed by various authors.

In the design proposed by I. C. Hunter [13], the equivalent circuit based on J-inverter network was introduced, and J-inverter values have been determined to obtain the optimum design parameters. The coupling coefficient between resonators has been derived and design parameters have been optimized to obtain minimum degradation of the passband performances [14]. Method of applying coupling matrixes [19] and new systematic approach [20] for the optimum design has also been reported.

In order to maintain the constant passband width within the tuning range, the method using stepped impedance line as shown in Fig. 2 has recently been proposed. It is known that in order to achieve the constant bandwidth within the tuning range, the coupling coefficient between the adjacent resonators must be inversely proportional to the frequency, while the external Q factors must be proportional to the frequency [14]. In the design as shown in Fig. 3 a coupling reducer is inserted in order to control the not only the center frequency but also the passband width. In Fig. 4 the tunable filter characteristics based on this design are shown [16].

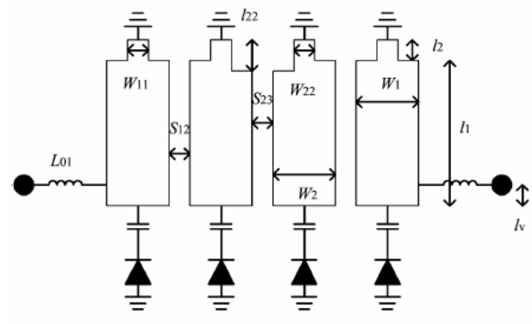


Fig. 2. The varactor tuned combline filter with constant passband width.

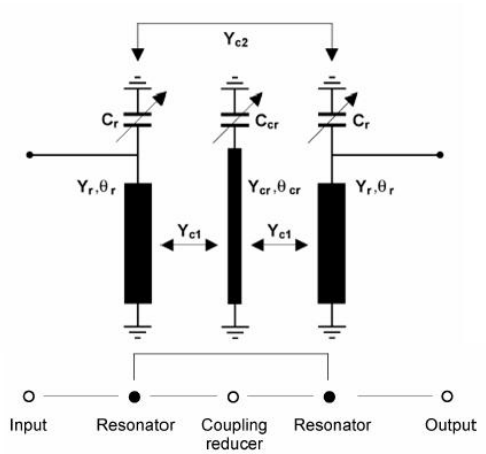
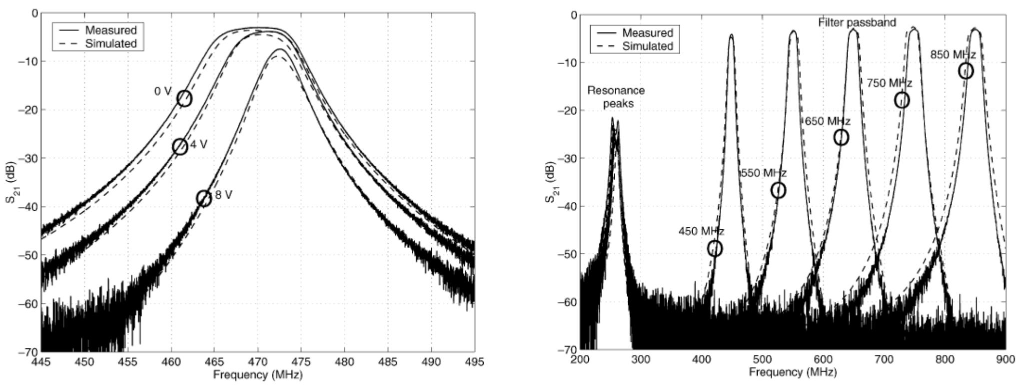


Fig. 3. The combline filter tunable in both the center frequency and the bandwidth.



(a) (b)

Fig. 4. The combline filter tunable in both (a) the bandwidth and (b) the center frequency.

B. The varactor tuned interdigital filter [22]

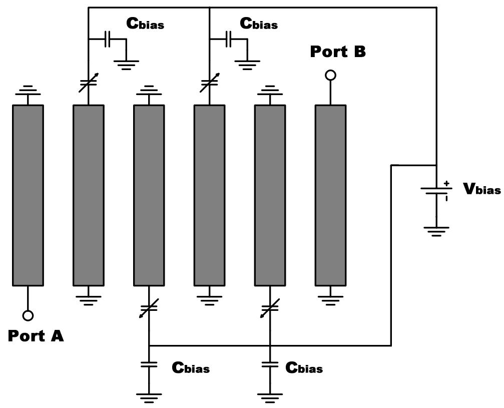


Fig. 5. The varactor tuned interdigital bandpass filter.

Typically, the interdigital configuration is as commonly used as that of the combline, because only short positions are different and the varactor diodes are loaded at the open ends as are in the combline configuration in Fig. 5. This configuration enables us to achieve wide tuning range more than 60% of its center frequency [22].

The center frequency of the filter is also determined by the resonance length of the line as well as the capacitance value of the varactor diodes which tune the resonant frequency. The quality factor of the resonator is a function of the line length as well as the series resistance of the varactor diode.

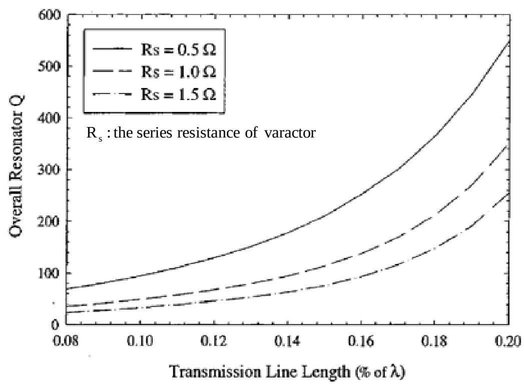
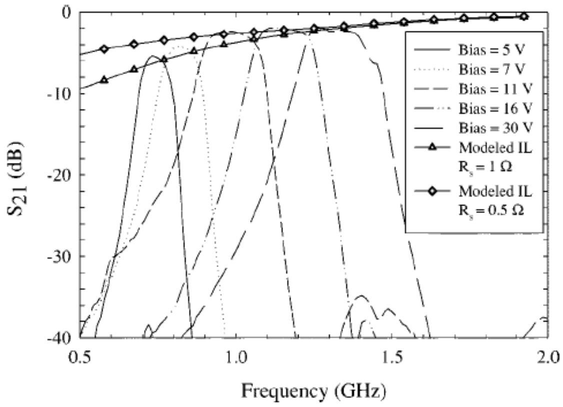


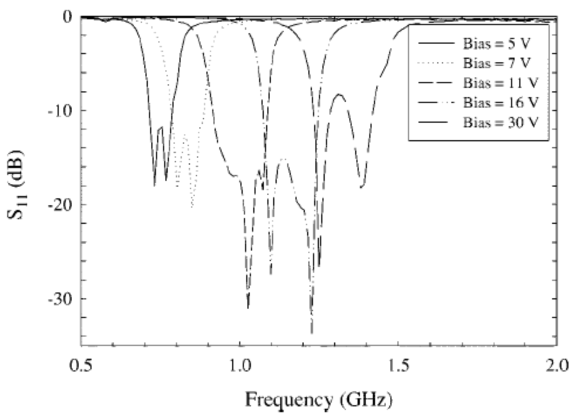
Fig. 6. The Q factor of resonator with varactor loaded line in Fig. 4.

Fig. 6. shows the overall quality factor of resonator with loading varactor. In order to improve the overall quality factor of the resonator, the varactor diode having a high quality factor and the relatively long transmission line must be used in the design. However, the tuning range is inversely proportional to the length of the transmission line. In addition, the higher voltage is applied to a varactor diode, the quality factor of the diode is improved, and the insertion loss characteristic is also improved. In Fig. 6 the Q factor of the varactor diode is pronounced, since the insertion loss decreases as the center frequency

goes higher.



(a)



(b)

Fig. 7. RF tunable filter, (a) measured insertion loss, and (b) return loss for various bias levels.

C. The varactor tuned filter using microstrip line ring resonator [23-32]

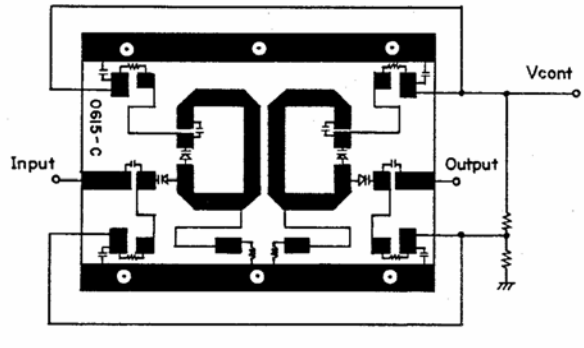


Fig. 8. The typical varactor tuned filter using microstrip ring resonator.

M. Makimoto proposed a tunable bandpass filter using microstrip ring resonators [23]. The resonator is composed of transmission line and varactor diode located between the ends of the line shown in Fig. 8. This configuration gives relatively wide tuning range and steeper skirt frequency characteristics due to transmission zeros introduced by series resonance near the passband as shown in Fig. 9. The bandwidth of the second-order filter is controlled by tight coupling characteristics between two rings shown in Fig. 8 [24-32]. From the input admittance of resonator, the parallel and series resonant frequency can easily be derived. The initial electrical length of resonator can be calculated by the parallel resonant condition.

In the other design method suggested by Al-Charchafchi [28] and T.S. Martin [25] [31], the equivalent circuit parameters of a ring resonator are derived and applied to the filter design.

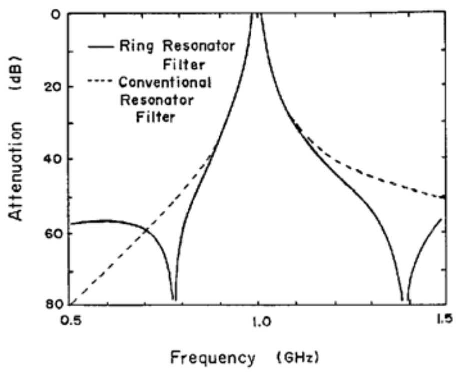


Fig. 9. The typical varactor tuned bandpass filter using microstrip line ring resonators.

D. The varactor tuned hairpin filter [33-34]

Since the hairpin filter is more compact than the other configurations, it can be applied to miniature systems. The tunable bandpass filter shown in Fig. 10 was proposed by Matthaei, G.L. [33] and has an octave band tuning range together with a compact size.

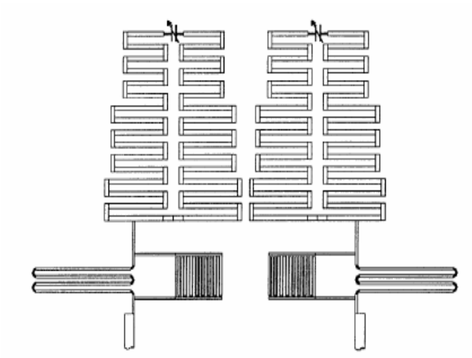


Fig. 10. The varactor tuned hairpin filter proposed by Matthaei[33].

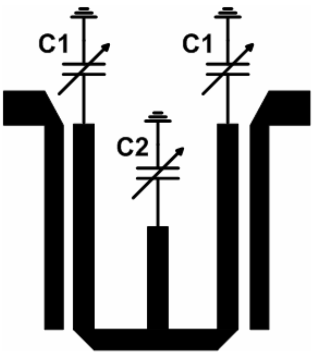


Fig. 11. The second-order varactor tuned hairpin filter[34].

Fig. 11 shows a modified hairpin tunable bandpass filter [34] which is composed of a half wavelength microstrip resonator and a tapped open stub. It is interesting that it has the second order response, while it has the size of first order filter. T-junction with a tapped open stub functions as equivalent K-inverter, and the bandwidth of filter is dependent on the transmission line length and varactor (C_2) of that. The center frequency of filter is also dependent on the resonator loaded varactor (C_1). Therefore, the center frequency as well as the bandwidth of filter can be tuned as given in Fig. 12. And regardless of tuned frequency, the bandwidth remains almost constant as shown in Fig. 13. However, this configuration does not have wideband performances due to a fixed input coupling capacitance.

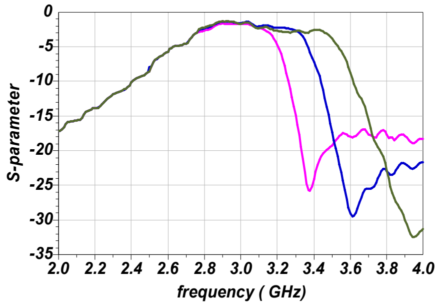


Fig. 12. The change of the bandwidth as varactor C_2 varies.

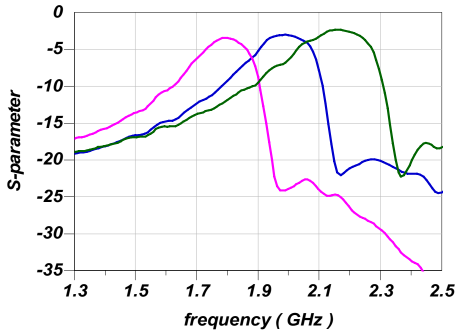


Fig. 13. The change of the center frequency as varactor C_1 varies.

III. Design of active tunable filters

A major drawback of passive tunable filters using varactor diodes is that they suffer relatively high insertion losses due to low quality factors of diodes, especially when narrow band designs are required. In order to compensate the loss, the negative resistance introduced by active elements is added to the filter network. In this section, the principles as well as the configurations of the typical active tunable filters will be discussed. In the design of active filters, the stability is the primary concern and the nonlinear characteristics as well as noise figures introduced by active elements must be fully analyzed in the design stage.

A. Active tunable combline filters [35-36]

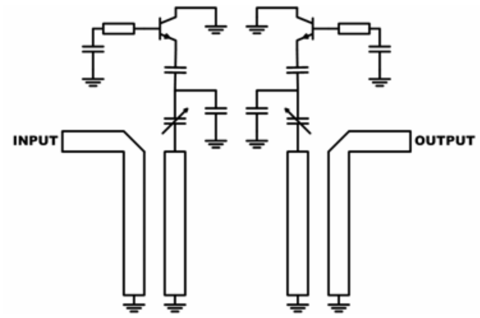


Fig. 14. The active tunable combline filter.

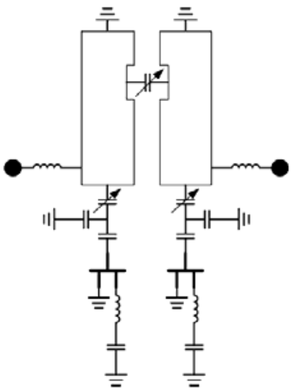
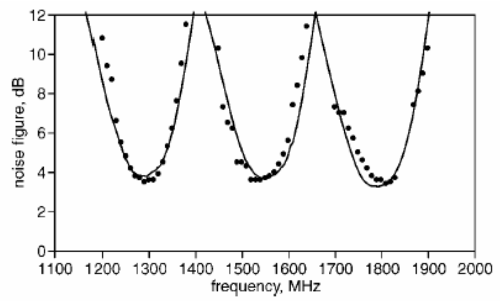


Fig. 15. The active tunable combline filter which has a constant tuning bandwidth.

In Fig. 14 and Fig. 15 two typical active tunable combline filters [35-36] are shown. In these configurations the negative resistance characteristics are provided to compensate the loss introduced by passive circuits. The negative resistance is generated using BJTs as well as FETs in either common-collector or common-emitter configuration. In case the negative resistance is too high, there exists the instability in the circuit. Therefore some gain compensation scheme must be used in order to guarantee the stability of the filter network depending on the temperature and other external factors. In the design given in Fig. 14 active elements together with varactor diodes are used in the resonator section. By adjusting the coupling characteristics, one can tune the filter response within the tuning range without changing the fractional bandwidth. In Fig. 15 in order to maintain the constant passband width within the tuning range a coupling varactor diode is introduced [36]. Active filters suggested previously have suffered from very high noise figures. In [35], the noise figure of the active filter is about 5 dB higher than that of its passive counter part. However, noise performance has been improved by applying a new active configuration. The noise figure of the circuit given in Fig. 15 is comparable with its passive counter part because a low noise topology which uses a common-collector inductive and capacitive series feedback circuit is employed [36]. As shown in Fig. 16, one finds that there is little increase of noise compared with that of passive type. One can achieve better noise performances with HEMTs or GaAs FETs than with BJTs. The frequency performances of the filter configuration given in Fig. 14 are shown in Fig. 17. However, the intermodulation distortion characteristics must be considered, which is not a problem in the passive types. However, they strongly depend on the active elements used in the circuit



Dotted Line : measured NF of active tunable filter
Solid Line : measured insertion loss or NF of passive tunable filter

Fig. 16. Noise performances of second-order active tunable combline filter

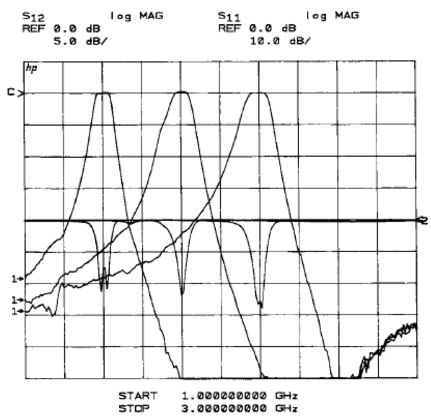


Fig. 17. Experimental performances (S11, S21) of varactor tunable filter in Fig. 14.

B. The active tunable filter using microstrip coupled line [37-41]

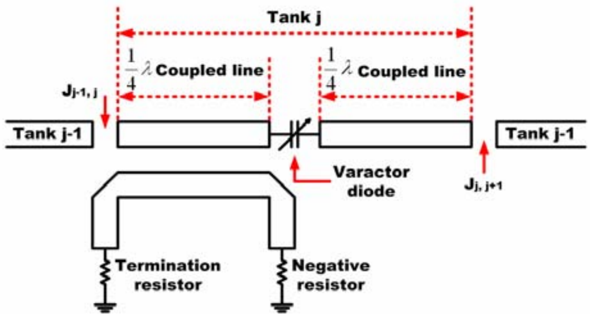


Fig. 18. The typical active tunable filter using microstrip coupled line.

Fig. 18 shows a typical end coupled line filter which includes the negative resistance circuit [38]. The negative resistance circuit which was described in the above section is introduced. The coupled line functions either as J- or as K-inverter. The resonator is coupled to an outside negative resistance (R_n) as shown in Fig. 19.

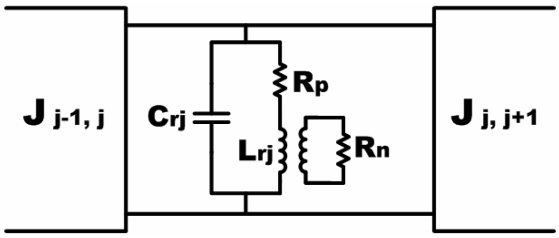


Fig. 19. An active resonator circuit coupled to a negative resistance.

By adjusting the coupling and the negative resistance (R_n), the parasitic resistance (R_p) can be canceled out in the active resonator and the Q value of the resonator can be improved, which results in improved insertion loss characteristics. Yamamoto [40] has proposed distinctive methods to realize the negative resistance and improved the filter performances. The gain degradation is improved by employing a symmetric coupled line as illustrated in Fig. 20. Fig. 21 shows its improved frequency response.

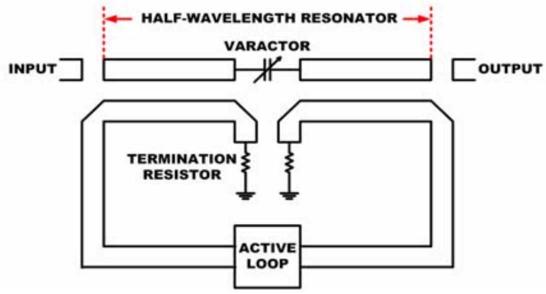


Fig. 20. An improved active tunable filter using microstrip coupled line.

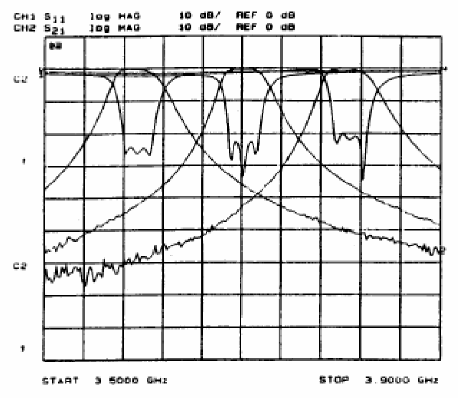


Fig. 21. The measured performances of the active tunable filter using microstrip coupled line in Fig. 20.

C. The active tunable filter using MMIC [42-48]

The active MMIC tunable filters employ active resonators in which the loss is compensated using negative resistance as discussed in B [42-48]. For miniaturized designs lumped elements together with active devices to generate the negative resistances are combined to realize the resonators [42-46]. The quality factor of a resonator using MMIC passive components is quite low due to its small volume. In order to improve the quality factor, an effective method was also proposed [46]. The methods for the noise optimization and automatic frequency tuning are proposed by Kaunisto [42] in Fig. 22, R, Tanne, G. [44], and Vladimir Aparin, [45].

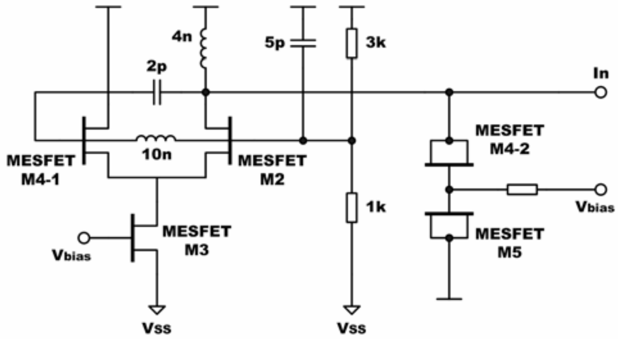


Fig. 22. The active MMIC tunable resonator.

In the frequency region above the K-band, active MMIC tunable filters in which the GaAs FETs and HEMTs are used to generate the negative resistance have been reported by Paul, D.K. [47] and Kang-Wei Fan [48]. In [47] active ring resonators loaded with varactor diodes are used at 12.5 GHz range , while in [48] the lumped elements are employed to design an active filter at K-band. As discussed in the previous section, the stability, noise figure, intermodulation distortion and current consumption of the filters must be considered, while the conventional passive ones do not require such considerations.

IV. Conclusions

We have discussed the design concepts as well as the performances of passive and active tunable bandpass filters of various configurations. In order to be applicable to the next generation mobile communication systems, there are several requirements such as reconfigurability, miniaturization and high performances. In case of narrowband applications the active filters seem to be better choice even though there are key problems to be solved such as stability, imtermodulation distortion and power handling capability.

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