An Overview of Filter Integrated Switch (FIS) for RF and Microwave Applications

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***Abstract*— Integrating multiple devices into one single device is an effective method to reduce circuit size, mismatching loss, and fabrication cost. Radio frequency (RF) and microwave device integrated with filter have become a popular design concept in the recent years. In this paper, an overview of the filter integrated switch (FIS) for RF and microwave applications is presented based on previously published studies and research journals starting from 2006 until 2016. This paper also emphasizes the use of previous and current development of filter integrated switches which mainly covers the fundamental concept on the FIS, the research trends in designs and developments. At the end, this paper reports on the variety of applications that can greatly benefit from FIS and some challenges and factors that need to be considered in designing and development of filter integrated switches.**

***Index Terms*— Bandpass Filter; Filter Integrated Switch; SPDT Switch; Switchable BPF.**

I. INTRODUCTION

A switch technology alone is responsible for both power consumption and size reduction in modern radio frequency instrumentation. Generally, radio frequency (RF) microwave switches can be divided into two categories which are the solid state switches and electromechanical switches. PIN diode is one of the primary solid state switches which are known best for its capability of offering high power handling along with high speed switching. Another one is the field-effect transistor (FET) switches. MESFETs and MOSFETs are the two commonly used FET types in integrated solutions for the industry nowadays. This is because of its voltage-dependant switching behaviour. Meanwhile, on the other side, electromechanical (EM) switches use a metal contact to make or break the switch connection. This mechanism promotes a low insertion loss with high isolation and also a high level of linearity which commonly important in high frequency equipment and applications. From these various types of switches with many benefits to offers, the choosing of a switch will come back to the fact of the switching requirements of the desired system itself [1].

Since microwave filters are also equally important components with major function in the development of various microwave system applications, especially the implementation of the filter in a wireless communication system, it requires a high performance filter with high selectivity, sensitivity and isolation filter. Thus, it is important to design the filter to have a desirable and suitable performance. To obtain high performance filter operation, there are numbers of important and crucial specifications that need to be implemented and achieved in designing the filter. The high performance characteristics of a microwave filter can be achieved by improving and analyzing the specifications parameter mainly the frequency range, bandwidth, return loss and also the insertion loss [2].

In corresponding to emerging development in microwave filter design, it becomes changeling as the demands and tight requirements for miniaturization, low production cost and also conservation of frequency spectrum keeps increasing day by day. As both microwave switch and a bandpass filter are two of the essential components in common current wireless communication systems, the concept of integrating both the filter to the microwave switch as shown in Figure 1, was introduced as one of the solutions to the problem. It was introduced mainly to adapt to the current trend and challenges stated previously such as the demand for higher quality performance and multifunction integration, a compact small-sized or miniaturize circuit and lower production cost which is always become the greatest interest in the most of the industry [3].

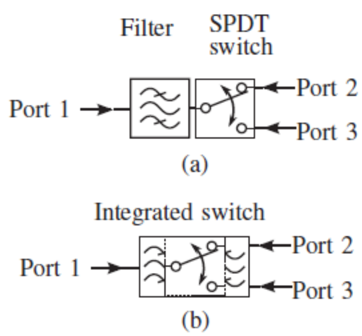

Figure 1: Conventional (a) filter and switch, (b) integrated filter switch [4].

The major benefit that can be obtained from integrating both the filter and the switch to become a single functional component is that the interconnection loss can be assumed as non-existing between the RF switch and also the filter [5,6]. Furthermore, the integration of this two components can directly reduce the overall circuit size as two separate components are combined by means of integrated into a single working component [7]. Thus, a compact and smaller size circuit can be obtained compared to the conventional separated or cascaded microwave switch and bandpass filter

[4]. Meanwhile, on the aspect of the overall performance of the system, the benefit from integrating both components is that the losses from each of the component are directly combined with each other when both switch and filter are integrated and become as one form of system losses. Thus, it achieves a simplified form of total losses while maintaining the level of the overall system.

II. Development of Filter Integrated Switch

The first ever filter integrated switch concept was introduced in 2006 [5]. To propose a design of single pole single throw (SPST) passive field-effect transistor (FET) radio frequency (RF) switch integrated with quarter wavelength bandpass filter, a 1 GHz Chebyshev bandpass SPST FIS with insertion loss less than 2 dB and an isolation of 22 dB was obtained by using 5th-order short-stub quarter-wavelength topology as shown in Figure 2 and Figure 3 respectively. This first FIS design has successfully achieved its main objective which is to propose a simplified system design by performing the integration between two components.

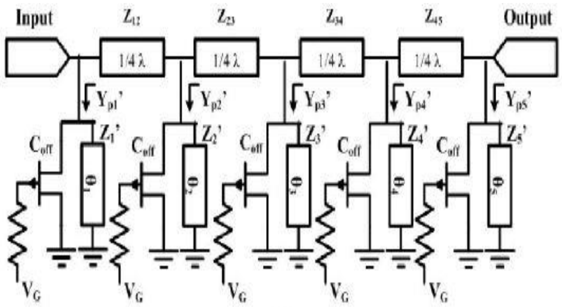

Figure 2: 5th-order SPST FIS [5]

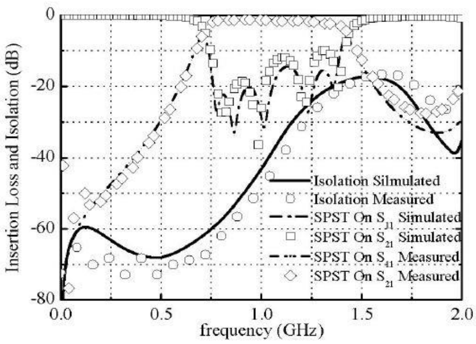

Figure 3: Measuremt during switch condition ON and OFF vs. frequency [5].

A Monolithic microwave integrated circuit (MMIC) Single Pole Double Throw (SPDT) switch integrated with 3rd-order bandpass filter was proposed in [8]. With an insertion loss of 3.1 dB at the center frequency and isolation higher than 30 dB obtained at the isolation port as shown in Figure 5, this FIS design used stepped-impedance resonators (SIR) with loaded HEMTs to develop the design at 40 GHz as in Figure 4. Moreover, in correspond to achieve a compact design, the SPDT switch is designed by the shared resonator technique between the two integrated SPST switch and thus results in a compact system in a single functional component.

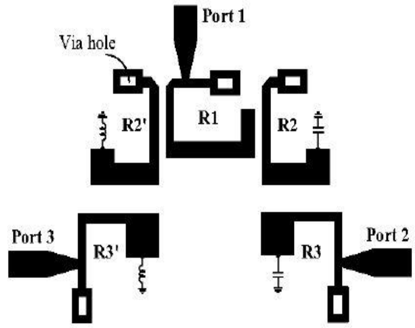

Figure 4: 3rd-order SPDT FIS [8].

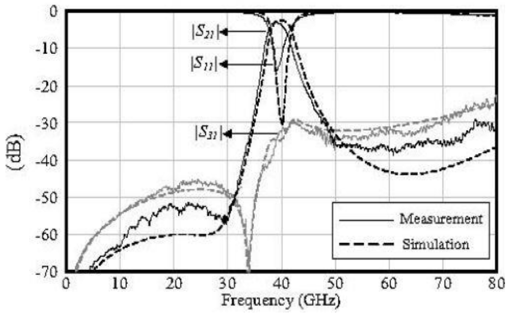

Figure 5: S-parameters results when ON (port 2) and OFF (port 3) [8].

Meanwhile, within the same year, a study in [9] came out with the integration of bandpass filter with the hybrid SPDT switch using FET as in Figure 6 and Figure 8. Furthermore, from Figure 7 and Figure 9, it can be seen that the two designs in this work achieved 1.5 dB insertion loss and 20 dB isolation at 1 GHz and 2.5 dB insertion loss and 27 dB isolation at 60 GHz. Not only expanding the implementation of FET to change from SPST to SPDT, but this work also introduced a method to provide a simple and precise way to develop an integration between quarter-wavelength bandpass filter and SPDT RF switch.

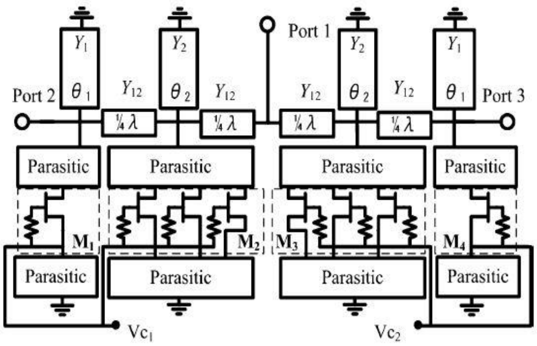

Figure 6: 1 GHz SPDT FIS [9].

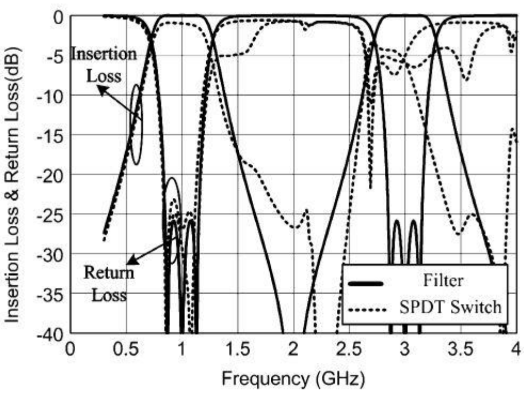

Figure 7: Frequency response comparison between the conventional filter and hybrid SPDT switch at 1 GHz [9].

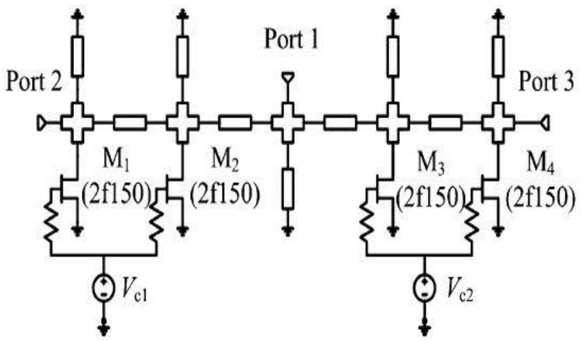

Figure 8: 60 GHz MMIC SPDT FIS [9].

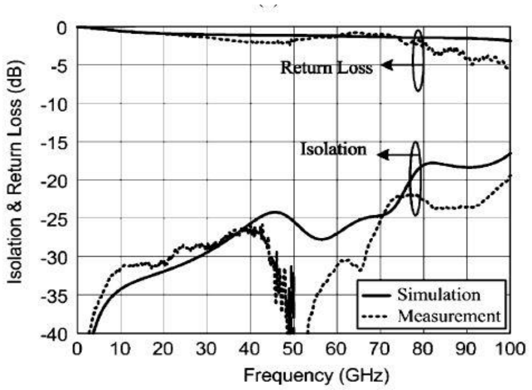

Figure 9: Isolation and return loss during OFF-state of the switch [9].

Then the development of filter integrated switch was further studied and in [10]. It successfully presented enhancement features of multiple-port bandpass filter when it is integrated with MMIC SPDT switch as shown in Figure 10. In this paper, the implementation of loaded quarter-wavelength SIR instead of half-wavelength SIR is due to the fact that by using quarter-wavelength, the span between the adjacent resonant frequencies is twice bigger and wider than the one using half-wavelength SIR. Thus, Figure 11 shows the measured isolations which are (for all measured ports) higher than 27 dB.

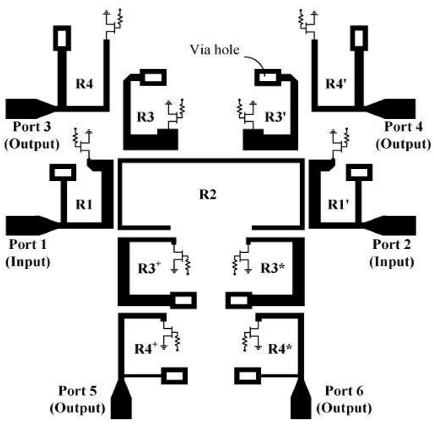

Figure 10: 4th-order six port FIS [10].

Further improvement of the filter integrating switch was introduced, where in the research, by referring to Figure 12, the size reduction of the FIS is given the priority [11]. By using the two concepts of reducing the size of the quarter-wavelength FIS, as shown in Figure 13, an insertion loss lower than 1 dB and isolation over 35 dB have been successfully obtained. In the development of the FIS in 0.15-um MHEMT process, the MMIC SPDT quarter wavelength bandpass FIS undergo size reduction from the shortening of the quarter wavelength series and shunt transmission line resonator which result in compact chip size of 2mm x 1mm.

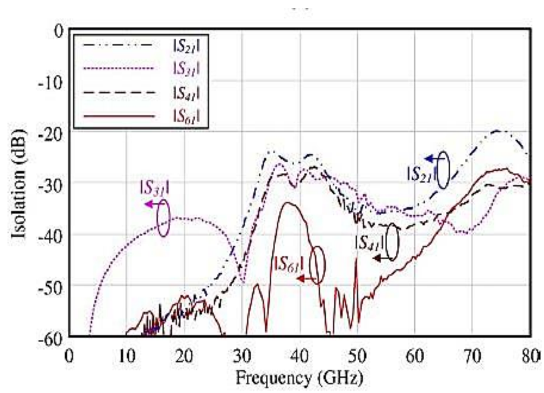

Figure 11: Result at the isolation port when port 1 and 5 are ON-state [10].

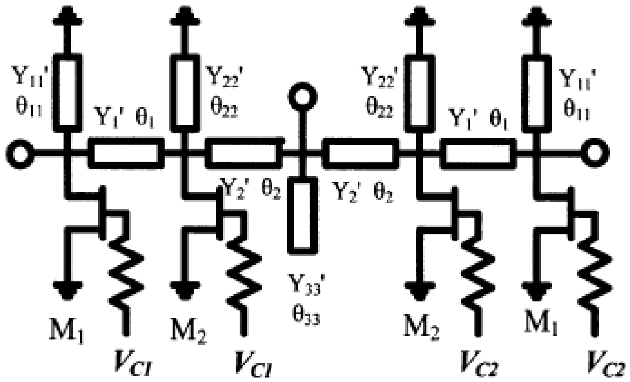

Figure 12: Reduced-sized SPDT FIS [11].

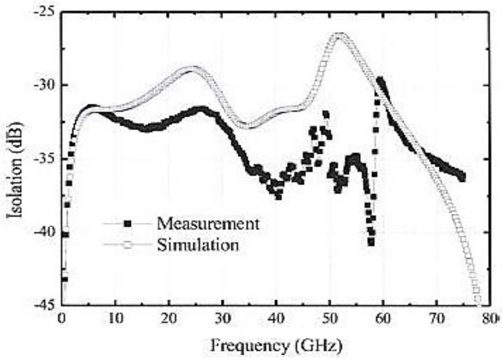

Figure 13: Measurement and simulation of isolation [11].

After the previous successful development of a reduced size FIS with improved performance, the research has been extended and studied in [6]. The additional PHEMT MMIC SPDT bandpass filter integrated switch for 50 GHz was proposed as in Figure 14 with 1.5 dB and 22 dB of insertion loss and isolation respectively. From the two demonstrated designs of FIS at 40 GHz and 50 GHz, it is shown in Figure 15 that under the same MMIC technology, the reduced-size FIS can operate at higher level of frequency if transistors having the same size are used since conventional travelling wave switch require small-size devices, and that leads to a reduced-size FIS at the similar cutoff frequency.

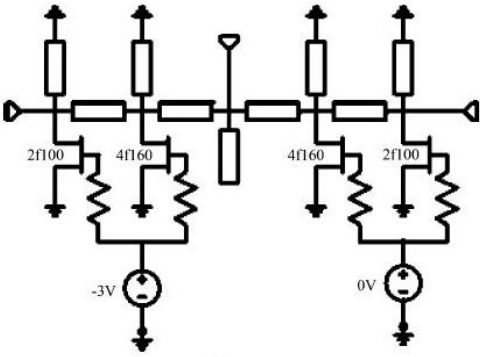

Figure 14: 50 GHz reduced-sized SPDT FIS [6].

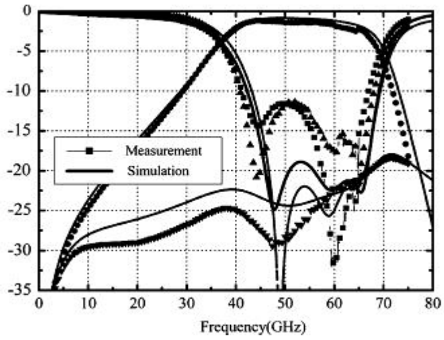

Figure 15: Measurement and simulation of S-parameters [6].

Meanwhile, research in [12] successfully presents an integration of PIN diode SPDT switch with a bandpass filter. In the research, a high level of isolation during the ON state of the switch and low insertion loss during the OFF state allow improvement in the overall system and contribute to reducing the noise figure of the system itself. It did not only eliminate the need for pre-selecting filter but this research also successfully proposed a high performance FIS with 1 dB insertion loss and 38.5 dB of isolation at 2.5 GHz frequency band.

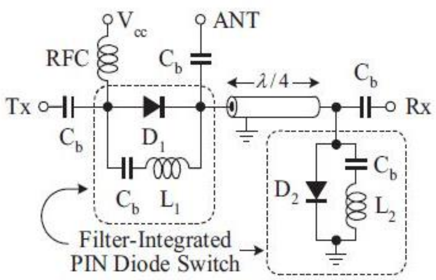

Figure 16: Filter-integrated PIN diode switch [12].

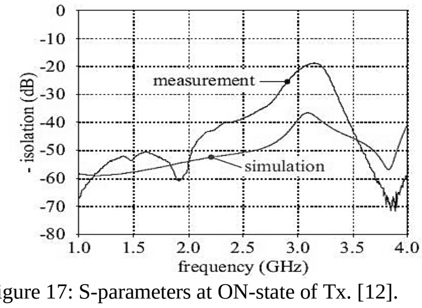

Figure 17: S-parameters at ON-state of Tx. [12].

The following year of 2010, filter integrated switch is extended to be electronically switchable and functioned as an SPST switch (shown in Figure 18) by introducing two shunt FETs at the capacitive loads in the depletion mode (D-mode) [13]. The capacitive-loaded short-ended hairpin resonator is utilized in the bandpass filter as it has a high density of metal-insulator-metal capacitor in the GaAs process. Thus, it can greatly contribute to the reduction in the required electrical length between the coupled-line and also the size of the filter itself while maintaining high isolation of 35 dB at 3.5 GHz by referring to Figure 19, in miniaturized chip size of 2mm x 1mm.

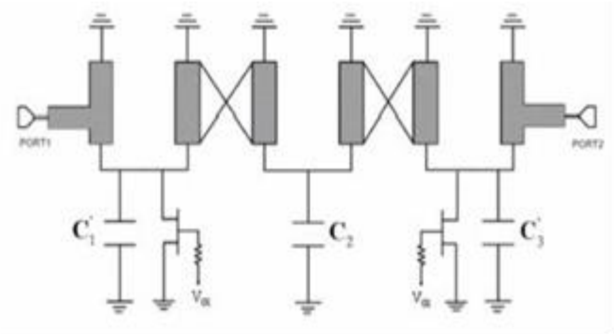

Figure 18: Switchable BPF [13].

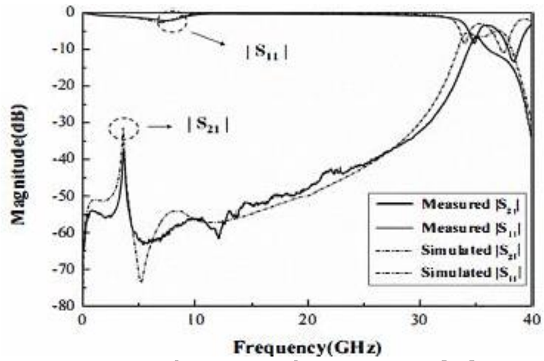

Figure 19: Filter response during OFF-state [13].

Next, filter integrated switch consisting a PIN diode of double poles double throw (DPDT) as in Figure 20 was successfully integrated with a bandpass filter within a single functional chip with an isolation of 42 dB at the frequency of 1.5 GHz (refer to Figure 21) [14]. In corresponding to the presence of unwanted spurious response and bad isolation performance at high frequencies, the defect-ground-structure (DGS) is introduced into the filter. Moreover, in this work, the 4th-order bandpass filter composing two symmetrical taped points at each I/O half-wavelength resonator connected to the feed line via p-i-n diodes to allow the circuit to select RF signal from two different antennas while rejecting the out-of-band interference within the system.

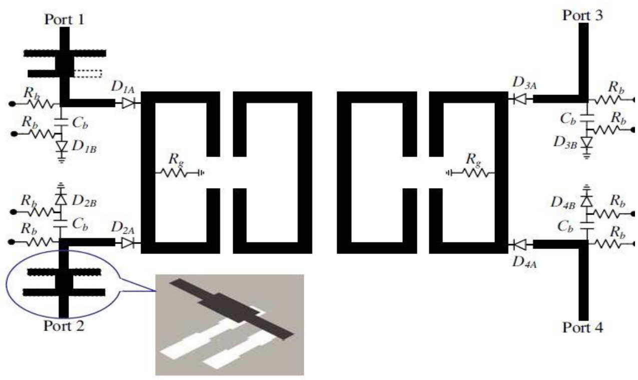

Figure 20: DPDT FIS [14].

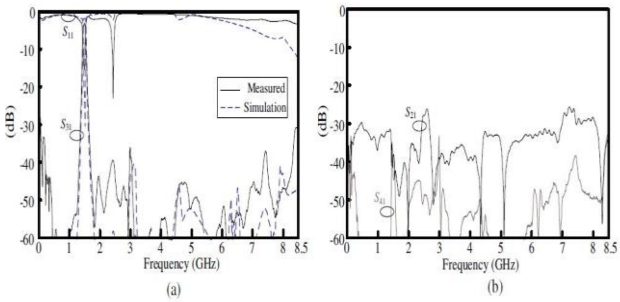

Figure 21: Measurement result of DPDT FIS [14].

A new technique of filter integrated switch was, then, developed and introduced in [15]. The new technique introduced was achieved by altering the original form of original PIN diodes and quarter-wavelength lines, where a reversed-biased capacitance of the PIN diodes and additional inductive components were used to transform the conventional transmit-receive switch to exhibits the response of a bandpass filter. This beneficial technique offered high performance of return loss and isolation which is 20 dB and 50 dB respectively in a bandpass response at 2.5 GHz. Meanwhile, the absorptive feature of this FIS is achieved by putting two single pole single throw (SPST) to form a single pole double throw (SPDT) switch and the presence of inductive components to cancel the reversed-bias capacitance of the diode.

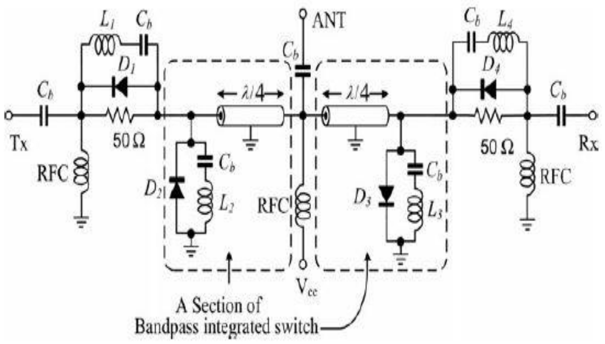

Figure 22: Absorptive bandpass FIS [15].

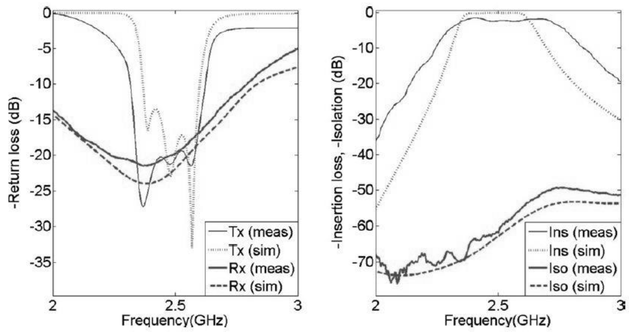

Figure 23: Results of absorptive bandpass FIS during Tx ON state [15].

The development of FIS was further realized in [16]. A 42 GHz MMIC single pole double throw (SPDT) bandpass FIS using HEMT loaded coupled lines was successfully proposed with measured insertion loss of 3.5 dB and isolation of 29 dB at the center frequency. The HEMT loaded coupled lines used in this work provided a necessary adequate coupling in the thru-state (ON) and generate transmission zeros in the isolated-state to improve the system isolation performance.

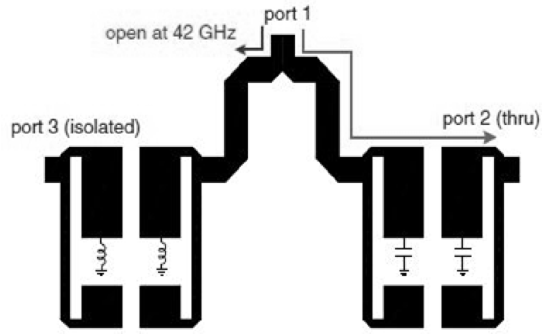

Figure 24: Bandpass filter integrated to SPDT switch [16].

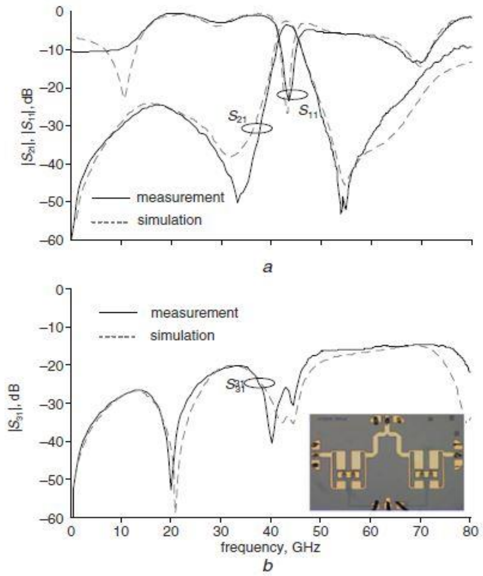

Figure 25: S-parameter results of SPDT FIS at thru port and isolated port [16].

By having an aim to obtain a fast switching speed and high linearity performance, [17] demonstrated a filter integrated switch which consists of single pole single throw (SPST) switch along with a bandpass filter that gave the final performance of 4.7 dB and 40.2 dB for insertion loss and isolation correspondingly. This was successfully achieved by using 0.18-um BiCMOS technology when cascading the series switches with the bandpass filter. While to increase the isolation in this circuit, the off state capacitance formed a parallel resonance with inductance and the parasitic capacitance of the off-state switch in another hand would form a bandpass filter with additional transmission zeros.

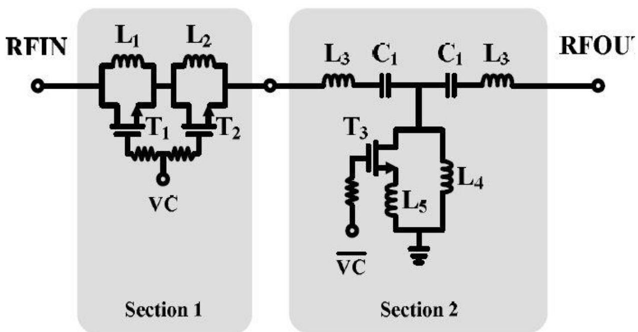

Figure 26: SPST bandpass filter integrated switch [17].

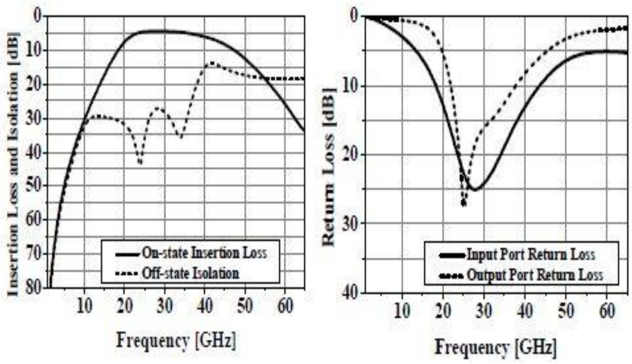

Figure 27: S-parameter for SPST FIS [17].

In February 2004, a compact single pole double throw (SPDT) switchable bandpass filter based on the concept of the multi-coupled line was introduced in [7]. A capacitive loaded multi-coupled line switchable bandpass filter is integrated into an SPDT RF switch, by replacing and substituting the structure of quarter-wavelength impedance transformer at the junction of a conventional design with a J-inverter. Besides a great reduction in the size of the overall circuit, the design also offers an insertion loss of 0.97 dB with isolation of more than 20 dB is achieved. Higher order filter response with improved selectivity performance can also be achieved by introducing more capacitive loaded transmission line resonators.

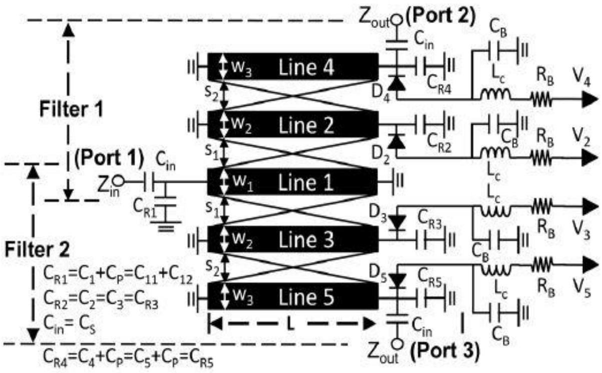

Figure 28: 3rd-order switchable SPDT bandpass filter [7].

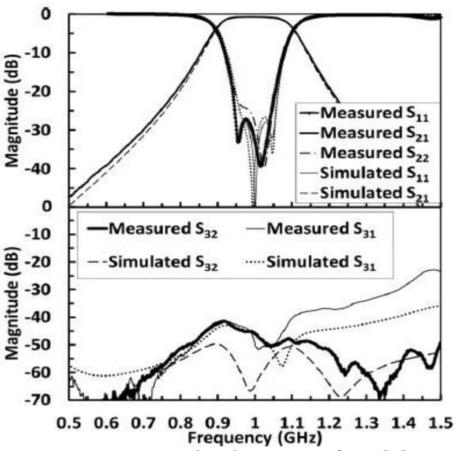

Figure 29: Narrowband response of FIS [7].

Next, in [4], X-band compact-sized SPDT bandpass FIS is presented as shown in Figure 30 with an isolation performance around 30 dB (refer to Figure 31). In this paper, the number of switching elements is greatly reduced to only two PIN diodes. By integrating the switch into a coupled microstrip line multi-section bandpass filter, a compact planar design is achieved successfully. Besides, the circuit in this work can be extended to a single pole multiple throw (SPMT) switch and a different response for different switching states can easily be altered by using a non-symmetrical design, thus making it a compact yet flexible form of a filter integrated switch.

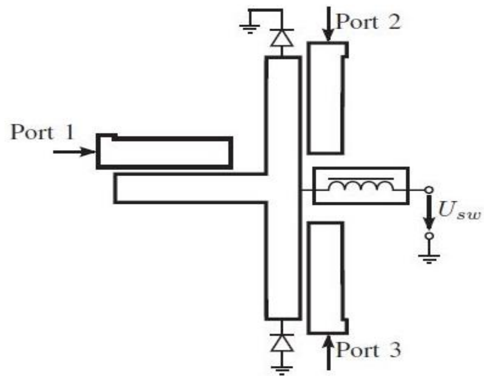

Figure 30: SPDT bandpass FIS [4].

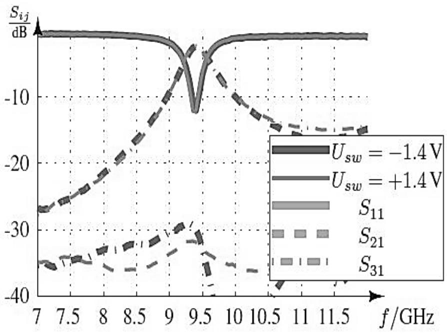

Figure 31: S-parameters for both ON and OFF states [4].

Recently in August 2016, filter integrated switches were taken to the next level when an absorptive switchable filter from allpass-to-bandpass was introduced in [18] with the additional features of having a constant group delay while processing multiple states of insertion loss. To successfully demonstrate the concept in this paper, as in Figure 32, 4th-order constant group delay switch bandstop filter was synthesised and designed. With the main objective of providing a solution to the group delay variation that occurs during the switching of the filter, by referring to Figure 33, a promising absorptive spurious mode insertion loss of 4.1 dB and isolation of 32.5 dB. In addition, a higher order of filter can be realized by cascading the N constant group delay switched-absorptive-bandstop filter to form a multi-channel switched filter bank.

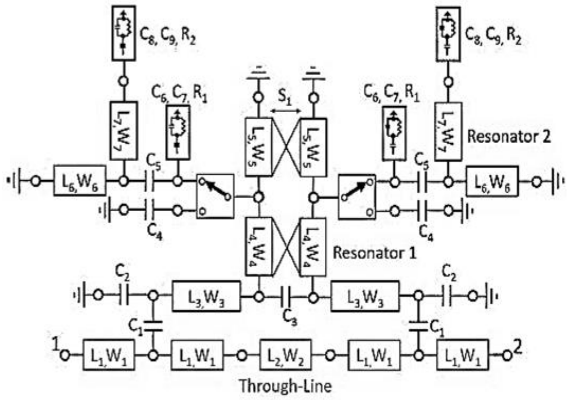

Figure 32. 4th-order SPDT reconfigurable bandstop FIS [18].

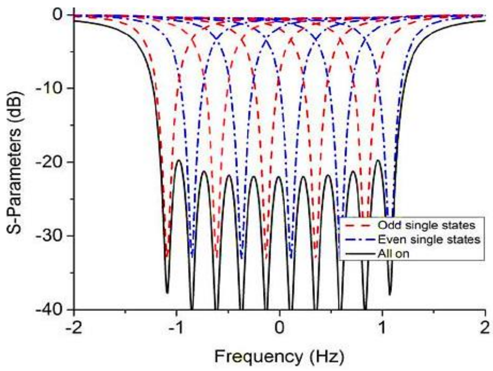

Figure 33: Insertion loss on all channels [18].

III. Application of Filter Integrated Switch

Filter integrated switches are implemented in various high frequency applications since it started being introduced in [5]. The general concept of the filter-integrated switch allows a systematic design approach to implement both the switch and the filter into one functional circuit. This also allows a smaller and reduced system size as shown previously in Figure 1. Therefore, wireless communication such as WiMAX [12,13], high power terminals system [15], including sensor and radar system [16] all consist of an integrated filter with switch circuit. FIS is also used in MIMO system as in Figure 34, to allow a selection of radio frequency signals from two available different antennas while rejecting any out-of-band interference [14].

Furthermore, filter integrated switch also can be utilized in radar system shown in Figure 34, as it offers a low insertion loss and high isolation with a high speed switching which is certainly are an important aspect that needs to be considered in the radar system, for pulse generation [17].

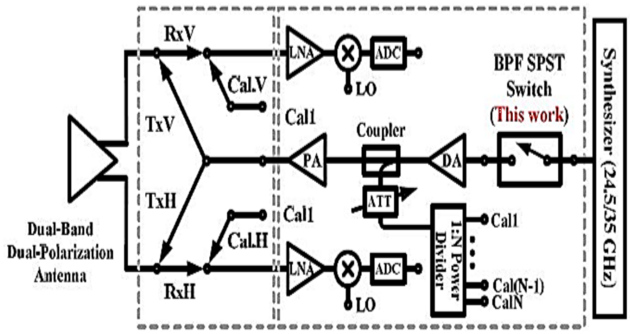

Figure 34: Dual-band antenna in pulsed radar system [14].

Common wireless broadband technology such as WiMAX, the use of T/R switches are preferable as compared to circulator due to the reason of the material of circulator itself which is ferrite. Not only the material is quite costly, but it also exhibits a high level of non-linearity which clearly is a crucial aspect of today's modern wireless communication systems. T/R switch, on the other hand, offers a lower cost with high linearity and isolation. Figure 35 shows the conventional circulator and switch for the duplex system [12].

Table 1
Summary of the Filter Integrated Switch Development.

Author(s)	Integration	Approach	Switching Element	Freq. (GHz)	Bandwidth	Insertion Loss (dB)	Isolation (dB)	Absorptive Feature
Jeffrey Lee et al. 2006 **[5]**	SPST-BPF	Short-stub quarter-wavelength	FET	1	-	1.3	> 22	No
Shih-Fong Chao et al. 2007 **[8]**	MMIC SPDT-BPF	Loaded stepped-impedance resonators	HEMT	40	3.2 GHz	3.1	> 30	No
Zuo-Min Tsai et al. 2007 **[9]**	MMIC-SPDT BPF	Shunt-resonators series quarter-wavelength	FET	60	300 MHz	2.5	> 27	No
Shih-Fong Chao et al. 2007 **[10]**	MMIC SPDT multiple-port BPF	Quarter-wavelength stepped-impedance resonators	HEMT	40	5.2 GHz	3.7	> 25	No
Jeffrey Lee et al. 2008 **[11]**	SPDT-BPF	Reduce-sized quarter-wavelength	0.15-µm GaAs mHEMT	30 – 50	20 GHz	< 1	> 35	No
Jeffrey Lee et al. 2008 **[6]**	SPDT-BPF	Reduce-sized quarter-wavelength	0.15-µm GaAs pHEMT	40 – 60	20 GHz	< 1.5	> 22	No
P. Phudpong et al. 2009 **[12]**	SPDT-BPF	Inductor parallel PIN diode	PIN diode	2.5	650 MHz	1.5	38.5	No
Wei-Hung Liao et al. 2010 **[13]**	Switchable SPST-BPF	Capacitive-loaded hairpin resonator	GaAs pHEMT	3.5	400 MHz	< 2.8	> 35	No
P. Phudpong et al. 2012 **[14]**	Absorptive SPDT-BPF	Multiple sections quarter-wave lines	PIN diode	2.5	105 MHz	2.3	50	Yes
S. F. Chao & M. W. Shih 2012 **[15]**	DPDT-BPF	Switchable feed lines and hairpin resonators	PIN diode	1.5	450 MHz	3.1	43	No
S. F. Chao 2012 **[16]**	MMIC SPDT-BPF	Loaded coupled-lines	HEMT	42	3.36 GHz	3.5	29	No
Donghyun Lee & Cam Nguyen 2014 **[17]**	SPST-BPF	nMOS transistor and inductor pairs	0.18-µm BiCMOS	35	13.5 GHz	4.8	> 32	No
Chang-Sheng Chen et al. 2014 **[7]**	Switchable SPDT-BPF	Capacitive-loaded multi-coupled line	PIN diode	1	100 MHz	< 0.97	> 20	No
Christian Rave et al. 2014 **[4]**	SPDT-BPF	Discrete PIN diodes and coupled microstrip line	PIN diode	9.4	450 MHz	2.4	30	No
Andrew C. Guyette et al. 2016 **[18]**	Absorptive SPST-FIS	Constant-group-delay switched resonator	Ultra-CMOS	1	119.5 MHz	4.1	32.5	Yes

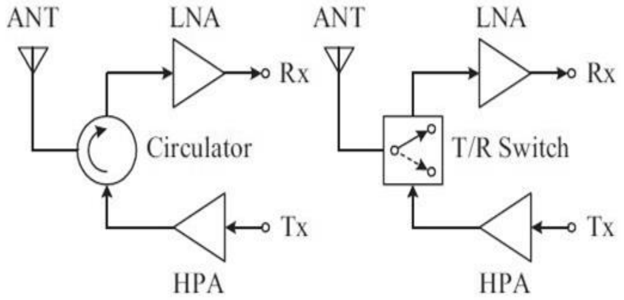

Figure 35: Conventional duplex system with a circulator or with a T/R switch [15].

IV. CHALLENGES IN DESIGNING FILTER INTEGRATED SWITCH

As presented in previous research conducted, the implementation of passive type switches such as the PIN diodes and FET have certain drawbacks to the overall system. One of the major drawbacks of these passive switches is that it can only be used for designing a wideband-application based system. The reason is that since the operating bandwidth is commonly exceeding 50%, it will result in larger bandwidth and thus decreasing the selectivity performance of the filter to provide good sharp band rejections [8], [10], [13] and [16]. Since the FIS is being developed to achieve better performance from time to time, power performance [5], [8-10], linearity performance [17], and potential interference [14-15] aspect, are also taken into consideration when designing the filter integrated switch.

V. CONCLUSION

In this overview paper of filter integrated switch, the fundamental theory of integrating a filter and a microwave switch into a single component, the design process and requirements, the detailed developments of filter integrated switch that first being introduced in 2006 until the present day, have been studied and reported in systematic chronological order. The main reason behind the introduction of this technique of integrating the two key components in transmit-receive (T/R) RF microwave system, is mainly to simplify and reduce the overall circuit in terms of size and design complexity. By referring to previous research, most of the reported designs of filter integrated switch use the common PIN diode and field-effect transistors (FET) single pole double throw (SPDT) microwave switch to be integrated with a bandpass filter. However, certain challenges have risen up when these passive switches possess over 50% bandwidth within operating frequency which causes them to only be applicable to wideband applications. In corresponding to this occurrence, the overall system will not have sharp out-of-band rejections. Due to this fact, many on-going filter integrated switch developments are conducted in order to adapt and full-fill the current demand of high isolation and absorptive FIS with a compact reduced-sized circuit of the narrowband system in advanced wireless communications and electronic industry.

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