A 0.1-to-1.2GHz Tunable 6th-Order N-Path Channel-Select Filter with 0.6dB Passband Ripple and +7dBm Blocker Tolerance

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Radio receivers should be robust to large out-of-band blockers with small degradation in their sensitivity. N-path mixers can be used as mixer-first-receivers [1] with good linearity and RF filtering [2]. However, 1/f noise calls for large active device sizes for IF circuits and high power consumption. The 1/f noise issue can be relaxed by having RF gain. However, to avoid desensitization by large out-of-band blockers, a bandpass filter (BPF) with sharp cut-off frequency is required in front of the RF amplifiers. g_m-C BPFs suffer from tight tradeoffs among DR, power consumption, Q and f_c. Also, on-chip Q-enhanced LC BPFs [3] are not suitable due to low DR, high area consumption and non-tunability. Therefore, bulky and non-tunable SAW filters are used. N-path BPFs offer high Q while their center frequency is tuned by the clock frequency [2]. Compared to g_m-C filters, this technique decouples the required Q from the DR. The 4-path filter in [4] has only 2nd order filtering and limited rejection. The order and rejection of N-path BPFs can be increased by cascading [5], but this renders a "round" pass-band shape. The 4th order 4-path BPF in [6] has a "flat" pass-band shape and high rejection but a high NF. This work solves the noise issue of [6] while achieving the same out-of-band linearity and adding 25dB of voltage gain to relax the noise requirement of the subsequent stages.

We propose a low-noise tunable 6th order N-path BPF with Chebyshev shape, high Q, high out-of-band linearity and high stop-band rejection. The idea is to substitute each LC tank in a capacitor-coupled-resonator filter with its N-path counterpart. However, this idea is not applicable due to the frequency dependency of the coupling networks. Instead, gyrators are used as coupling networks due to their wideband nature. A conventional singly-terminated 6th order LC BPF prototype is shown in Fig.1.a. The series LC tank can be converted into a parallel one by using two gyrators (Fig.1.b). The first gyrator G_1 is substituted by a single g_m cell to simplify the design by stagger tuning a 2nd and a 4th order BPF (Fig.1.b). Each LC tank can be emulated by an 8-path switched-capacitor filter shown in Fig.1.c [2]. In N-path filters, signals at $|(kN-1)f_{lo}|$ k=1,2,.. fold back to the pass-band of the filter [2]. Utilization of 8 phases greatly relaxes the folding-back issue. Each 8-path switched-capacitor bank is differential to suppress BPF transfer functions at even harmonics of the f_{lo}. Therefore, the next BPF transfer function will be at $3f_{lo}$. To save area, also each tank capacitor is differential. The schematic of the proposed filter is shown in Fig.2. The gyrator G_2 is similar to [7], but by making the feedforward path of the gyrator stronger than its feedback path while keeping the gyration ratio constant, the noise contribution of the gyrator is reduced while the gain of the filter is increased. Each g_m cell is a self-biased inverter. Switch resistances can de-Q the filter and therefore they should be taken into account in the design process. The extra phase shifts due to parasitic capacitors at node x and V_{out} of the filter distort the pass-band shape of the filter and cause more than 1.5dB of peaking. A miller-capacitor C_f is exploited to slightly lower the f_c of the first resonator while enhancing the bandwidth at V_{out} to reduce the effect of parasitic capacitors on the filter. The simulated effect is shown in Fig.3.a. The filter can achieve excellent out-of-band linearity because of: 1) the first section being "passive" (so the first g_m already receives a 2^{nd} order filtered signal) and the further filtering in the subsequent stages; 2) the very linear differential I/V characteristic of an inverter when loaded with low impedance. The filter can attain a low NF because of: 1) the exploitation of asymmetric gyrators; 2) a relatively high value of g_{m1}; 3) the utilization of a very small amount of negative admittance at node x and V_{out}; 4) a low switch resistance; and 5) the usage of 8 phases (less harmonic folding of noise).

The filter was realized in 65nm LP CMOS. The values of g_{m1}, g_{m2} and g_{m3} are 60mS, 24mS and 4mS respectively and made with minimum channel length transistors. C_1, C_2 and C_3 are 63pF, 53pF and 43pF, respectively. Each tank capacitor is a combination of MOM and accumulation-mode NMOS capacitors to increase its density. The 50Ω measurement interface is depicted in Fig.3.b. Two common-drain buffers are used for S_{21}, NF, IIP_3(OOB) and $B_{1dB,CP}$ measurements at port I. To measure the in-band linearity while not being affected by the buffers, a resistive voltage divider is used at port II. The switches are made of NMOS transistors with an on-resistance of 10Ω. The source and drain of each switch is biased to roughly 0.6V due to the self-biased inverters. The clock signals are ac-coupled to the gate of each switch which has a high ohmic resistor to a bias voltage of 0.75V. A divide-by-8 frequency divider is used to achieve 8 non-overlapping clocks. It should be noted that if the capacitor voltages of the third stage are taken as baseband outputs, the filter can be used as a receiver, taking benefit of the filtering properties. Because of its simplicity, the filter is easily portable to new CMOS generations.

The chip photo is shown in Fig.7 with an active area of 0.27mm^2. The tuneability of the filter from 0.1GHz-1.2GHz is shown in Fig.4. The pass-band ripple of the filter is <0.6dB. The negative resistances $R_{neg1,2}$ are slightly changed by tuning their supply voltages (<8%) over the tuning range, however without any modifications, the ripple is still less than 1dB (<0.5dB in the simulation) over the tuning range. Due to the use of small amount of negative admittance, the filter sensitivity to negative resistance values compared to conventional g_m-C filters [7] is reduced. The stop-band rejection of the filter is 59dB. The gain of the filter is 25dB (de-embedding the loss of buffers) and its bandwidth is 8MHz. The S_{11} varies between -5dB and -8dB, in the whole band. The measured NF for different f_{lo} is shown in Fig.5.a and is 2.8dB on average. The measured IIP_3(OOB) and $B_{1dB,CP}$ for different offset frequencies from f_{lo} is shown in Fig.5.b. The measured IIP_3(OOB) of +26dBm and 1dB blocker compression point $B_{1dB,CP}$ of +7dBm are achieved at Δf=50MHz. The measured transfer function of the filter at f_{lo}=1GHz with and without a blocker with P_{in}=2.3dBm located at Δf=20MHz from the center frequency, is shown in Fig.5.c. The filter draws 11.7mA and the LO chain draws 3 to 36mA from 1.2V in the tuning range. The LO feedtrough to the input port is less than -64dBm. The folding-back starts only from 7flo. However due to the mismatch, folding occurs at $3f_{lo}$ and $5f_{lo}$ with measured normalized gain of -54dB and -68dB, respectively.

The filter is compared with state of the art integrated filters [3-4,6] and complete receivers [5,8-9] in Fig.6. Compared to [4], much better pass-band shape, selectivity and stop-band rejection are obtained. Compared to [5], better out-of-band linearity, filter shape and NF are accomplished. Compared to [6], the NF is improved by more than 7dB. To our knowledge, this is the first integrated filter that can be used as a channel-select SAW-LNA hybrid which is tunable over a decade in frequency.

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Captions:

Fig.1: a) A conventional singly terminated 6th order LC BPF b) Exploitation of gyrators to transform a series LC tank to parallel one c) each LC tank is emulated by a differential switched capacitor 8-path filter

Fig.2: Schematic of the proposed widely tunable 6th order g_m-switched-C BPF

Fig.3: a) The simulated effect of C_f on the transfer function of the filter b) Measurement interface

Fig.4: The transfer function of the filter is tuned with a clock frequency from 100MHz to 1.2 GHZ. The upper figure shows the pass-band details in a span of 20MHz.

Fig.5: a) NF of the filter at different clock frequency; b) IIP_3 (OOB) and $B_{1dB,CP}$ for different offset frequencies; c) Transfer function of the filter at f_{lo}=1GHz with and without CW blocker with P_b=2.3dBm located at Δf=20MHz from center frequency

Fig.6: Comparison table

Fig.7: Chip micrograph

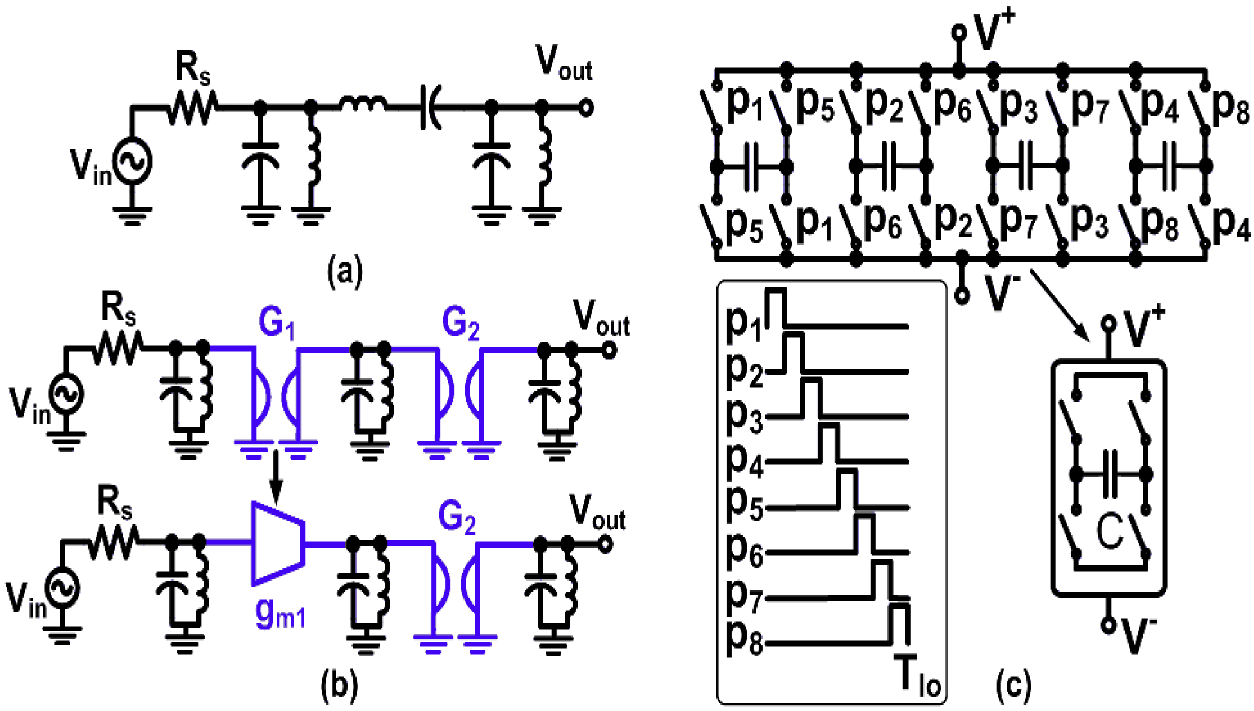


Fig.1: a) A conventional singly terminated 6^{th} order LC BPF b) Exploitation of gyrators to transform a series LC tank to parallel one c) each LC tank is emulated by a differential switched-capacitor 8-path filter

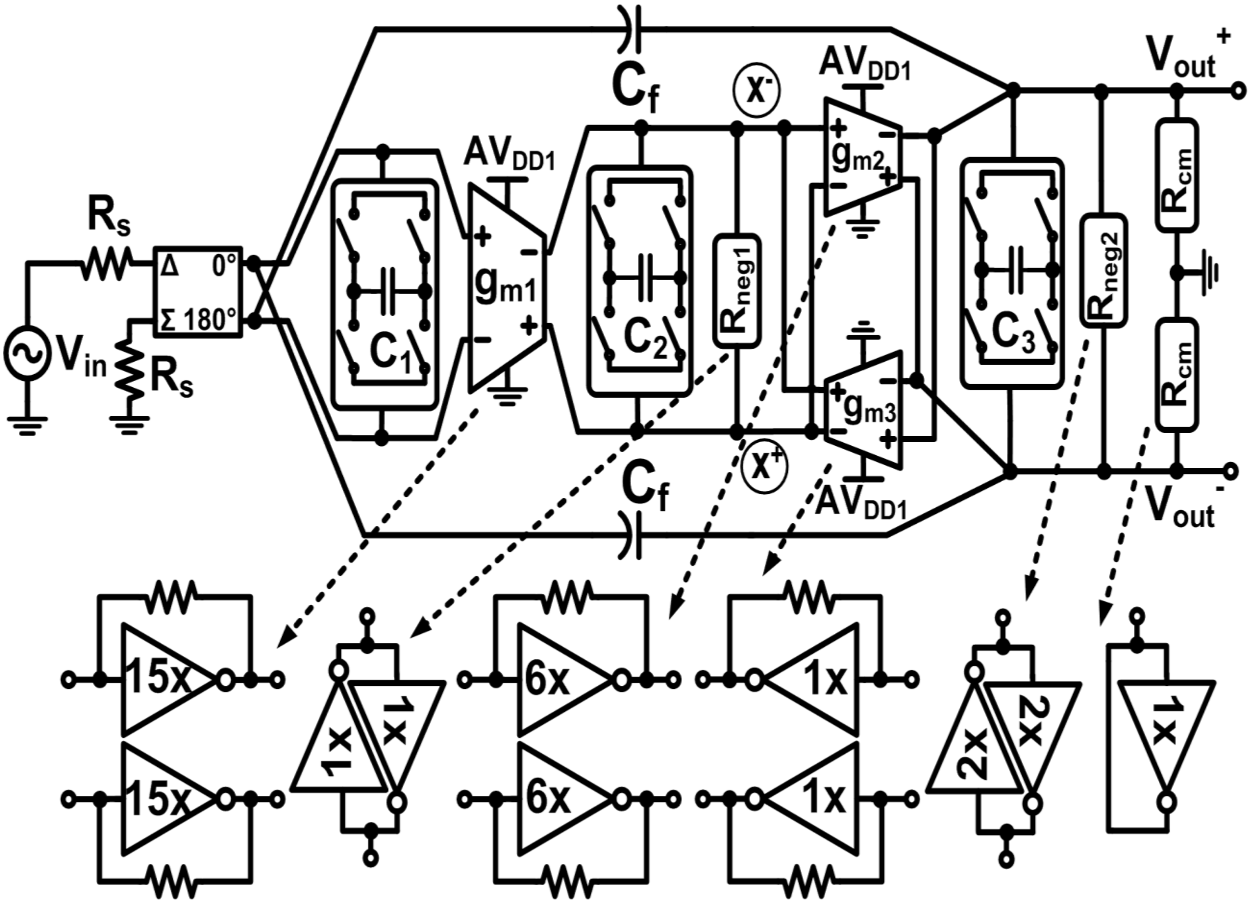
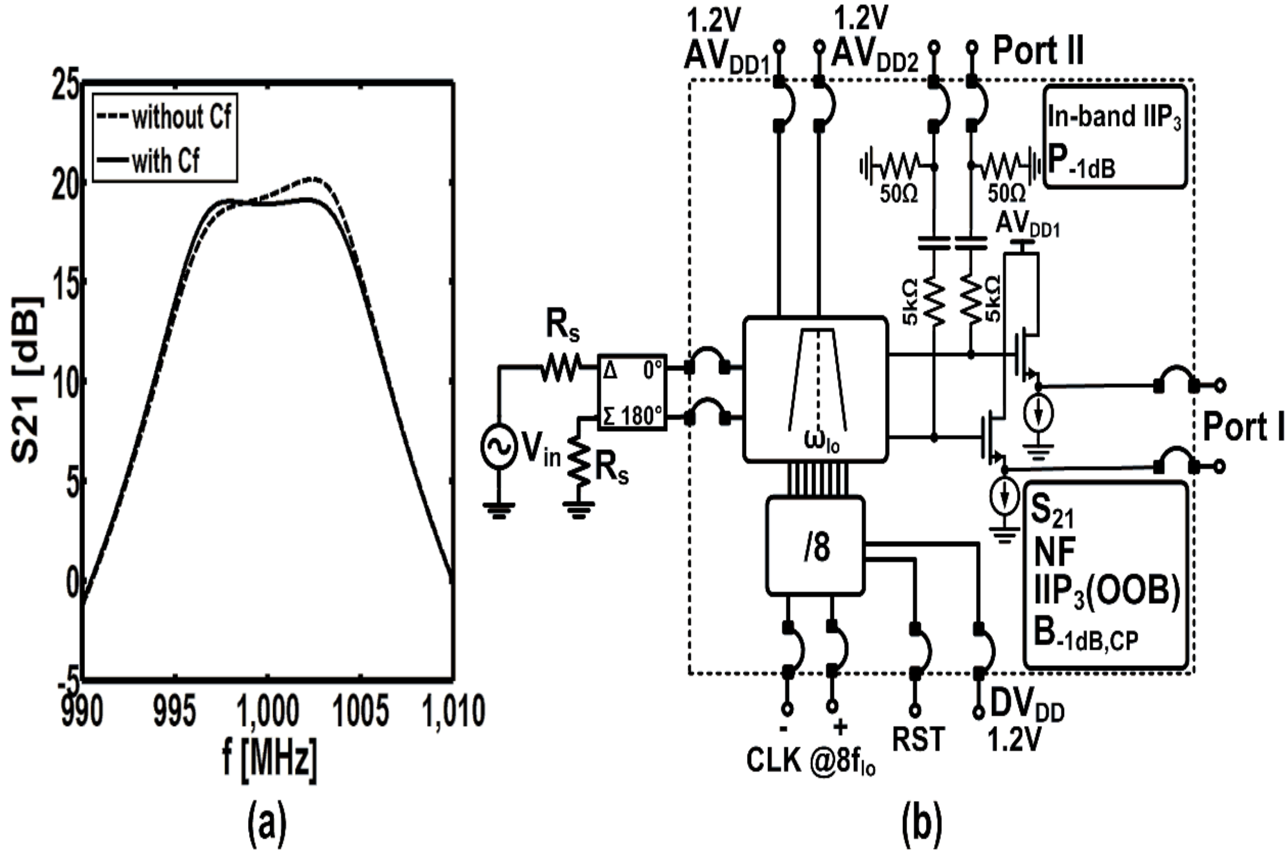


Fig.2: Schematic of a proposed widely tunable 6th order g_m-switched-C BPF



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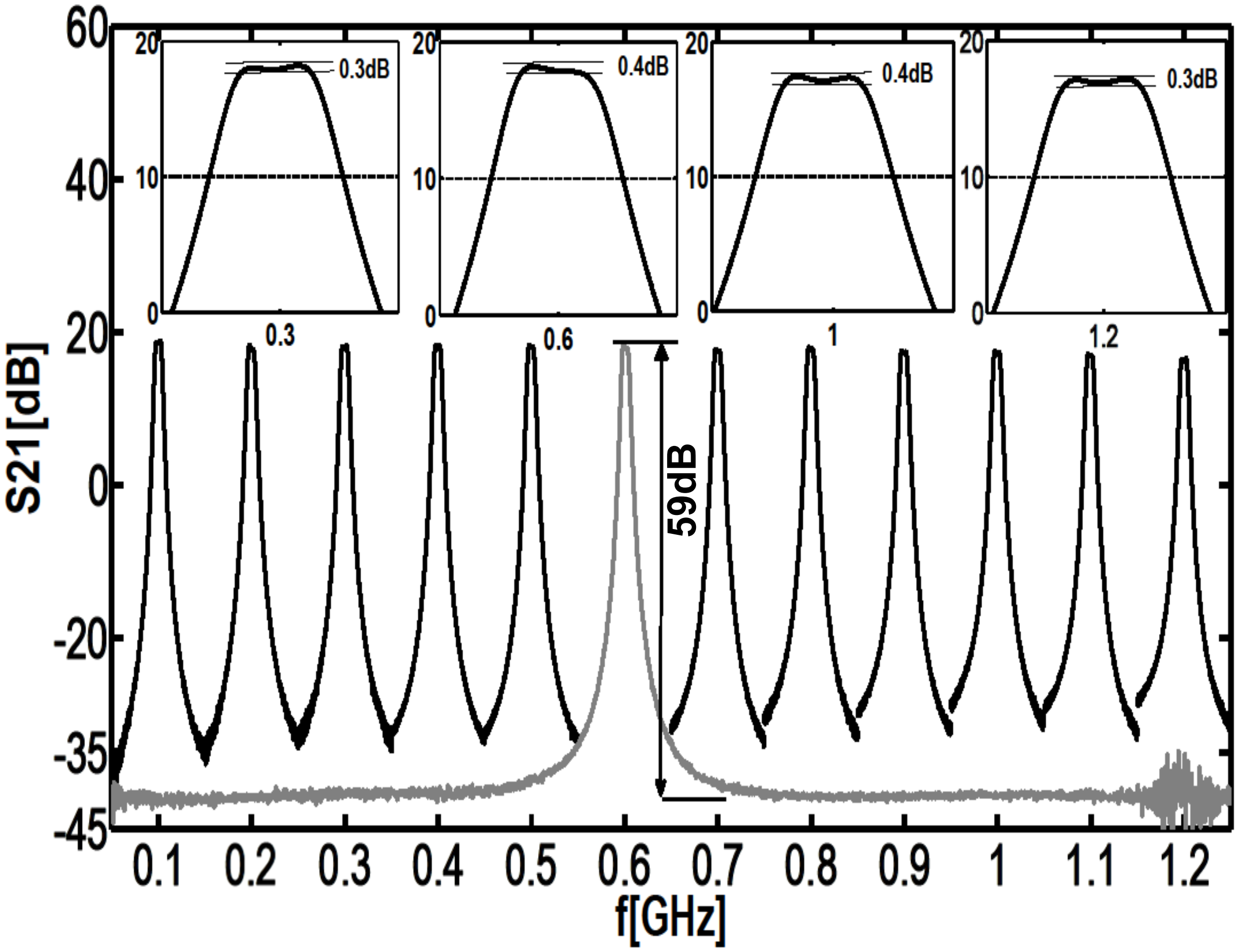


Figure 4: The transfer function of the filter is tuned with a clock frequency from 100MHz to 1.2GHz. The upper figures show the pass-band details in a span of 20MHz.

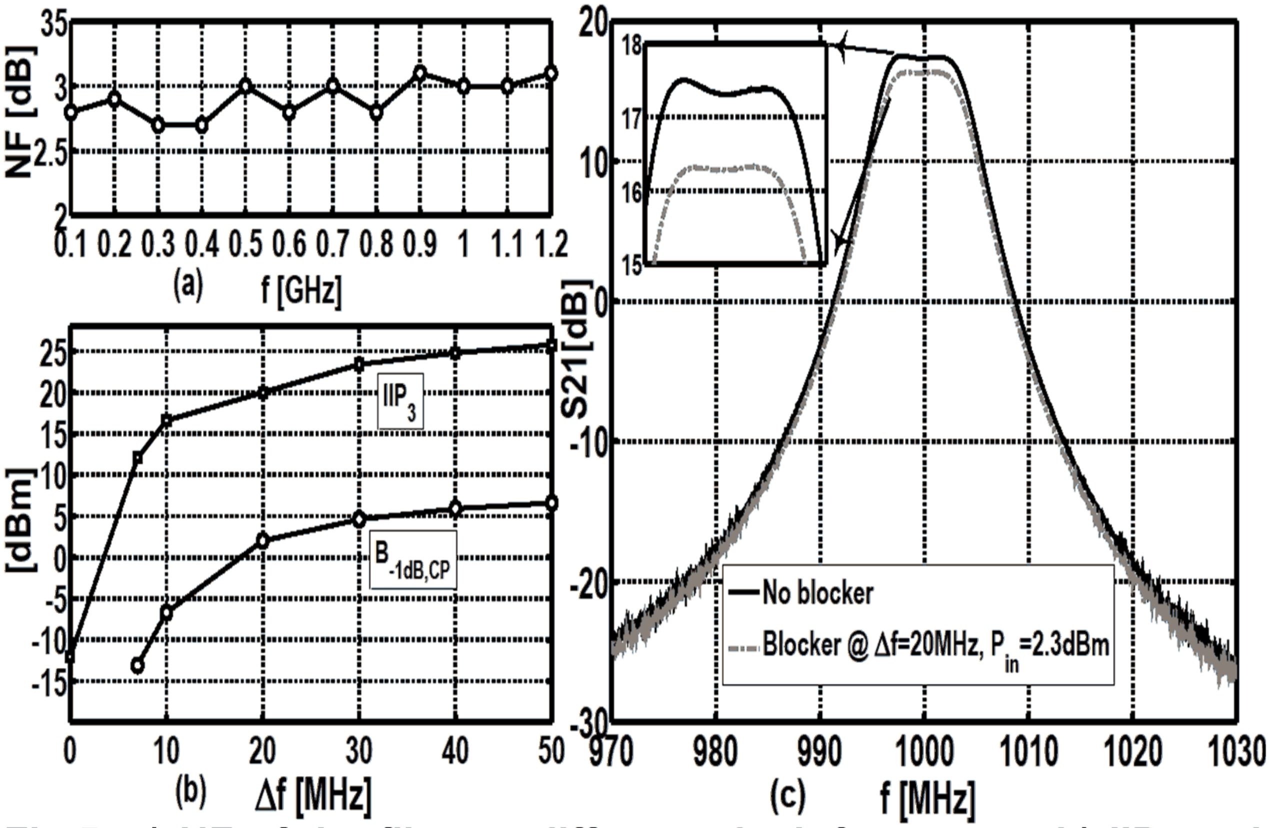
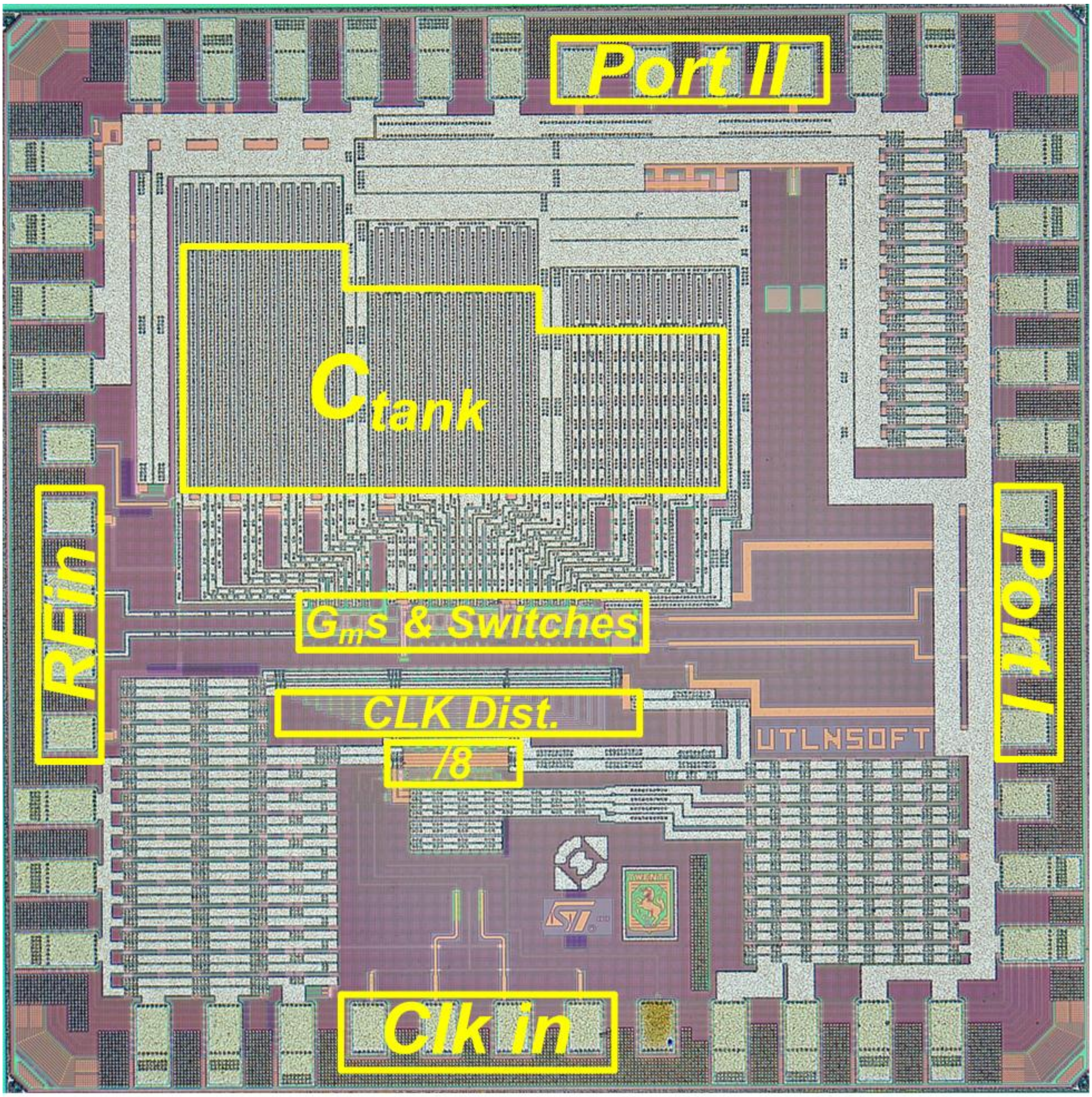


Fig.5: a) NF of the filter at different clock frequency; b) IIP_3 and $B_{1dB,CP}$ for different offset frequencies; c) Transfer function of the filter at f_{lo}=1GHz with and without CW blocker with P_{in}=2.3dBm located at Δf=20MHz from center frequency

	[This work]	Darvishi [6]	Soorapanth [3]	Borremans [8]	Mirzaei [5]	Murphy [9]
Circuit Type	Filter			Receiver		
CMOS Tech. [nm]	65	65	250	40	65	40
Frequency range [GHz]	0.1-1.2	0.4-1.2	2.14	0.4-6	2	0.08-2.7
IIP_3(OOB) [dBm]	+26	+28	N/A	+10	-6.3	+13.5
$B_{1dB,CP}$ [dBm]	+7	N/A	N/A	-8	N/A	<0
NF [dB]	2.8	10	19	3	5.8	2
Gain [dB]	+25	+3.5	0	+70	+55.8	+70
BW [MHz]	8	20	60	0.4-30	4	N/A
Ripple [dB]	<0.8	<0.4	0.7	-	-	-
Filter order	6	4	6	2 @RF	6	2 @RF
Stop-band rejection [dB]	50	>55	>30	<15 @RF	50	<15 @RF
Power [mW]	15-42mA	12.8-21.4	17.5	30-55mA	21mA	27-60mA
Area [mm^2]	0.27	0.12	3.51	2	0.76	1.2

Fig.6: Comparison table



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