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High isolation slot coupled antenna with integrated tunable self interference cancellation (SIC) Circuitry

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Submitted by: Haq Nawaz, Ozgur Gurbuz, Ibrahim Tekin

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Dear Editor-in Chief;

IET Electronics Letters

It is our pleasure to speak to you. Please find enclosed our Research Letter titled ***"High Isolation Compact Slot Coupled Antenna with Integrated Tunable Self Interference Cancellation (SIC) Circuitry"*** as a submission to *"**IET Electronics Letters**"*.

This letter presents a high interport isolation, compact dual polarized slot coupled monostatic patch antenna with integrated tunable analog/RF self interference cancellation (SIC) circuitry for 2.4/2.5 GHz In Band Full Duplex (IBFD) wireless applications. The presented antenna deploys hybrid feeding for improved interport isolation through polarization diversity and integrated single-tap RF SIC circuitry provides additional isolation on the top of antenna isolation. Brief mathematical description for deployed single-tap RF SIC is also presented. The implemented prototype of proposed antenna module provides around 80 dB interport isolation for 20 MHz bandwidth and better than 97 dB peak isolation when measured in lab in the presence of environmental reflections. Moreover, the 20 MHz SIC bandwidth with 80 dB isolation can be tuned within antenna's 10 dB return loss impedance bandwidth of 60 MHz.

We believe that the Implemented antenna module with small form factor having around 80dB T_x-R_x isolation within 20MHz bandwidth can be used to implement a compact 2.4/2.5 GHz IBFD transceiver in conjunction with just 30dB SIC at digital base-band stage. We believe that our paper is worth publishing in *IET Electronics Letters*. We are looking forward to your response.

Thanks.

Best Regards,

Prof. Dr. Ibrahim Tekin, Prof. Dr. Özgür Gürbüz and Dr. Haq Nawaz
Sabanci University
Electronics Engineering
Istanbul

High isolation slot coupled antenna with integrated tunable self interference cancellation (SIC) Circuitry

H. Nawaz, Ö. Gürbüz and I. Tekin

This letter presents a high interport isolation, compact dual polarized slot coupled monostatic patch antenna with integrated tunable analog/RF self interference cancellation (SIC) circuitry for 2.4/2.5 GHz In Band Full Duplex (IBFD) wireless applications. The presented antenna deploys hybrid feeding for improved interport isolation through polarization diversity and integrated single-tap RF SIC circuitry provides additional isolation on top of antenna isolation. Brief mathematical description for deployed single-tap RF SIC circuitry is also presented. The implemented prototype of proposed antenna module provides around 80 dB interport isolation for 20 MHz bandwidth and better than 97 dB peak isolation when measured in lab in the presence of environmental reflections. Moreover, 20 MHz SIC bandwidth with 80 dB interport isolation can be tuned within antenna's 10 dB return loss impedance bandwidth of 60 MHz.

Introduction: In Band Full Duplex (IBFD) radio transceiver based on monostatic patch antenna architecture has potential to double spectral efficiency through simultaneous transmit and receive operation at same frequency band [1]. However, desired performance of IBFD transceiver requires large amount of self interference cancellation (SIC) on receiver side in order to successfully detect very weak received signal of interest (SOI) [2]. The required amount of SIC can be determined through very simple link budget calculations by using transmit power, bandwidth and noise figure of the receiver [2]. For instance, with +20 dBm T_x power, 20 MHz R_x signal bandwidth and 10 dB noise figure of receiver, more than 110dB SIC is required [2].

Successive SIC stages are used as no single technique/stage is able to achieve required amount of SIC for realization of IBFD operation [2-3]. However, a high amount of SIC should be achieved in RF domain (antenna isolation + RF SIC circuitry) at transceiver front end in order to prevent saturation of receiver from high power SI signal [1-2]. The RF SIC circuitry is also very useful to suppress non-linear SI from T_x chain in addition to suppress SI resulted from environmental reflections. Compact high interport isolation antenna with tunable RF SIC is very useful to implement IBFD transceiver with reduced complexity.

In this letter, we have presented an antenna module which achieves very high T_x-R_x isolation through combination of orthogonal linear-polarization with hybrid feeding and integrated tunable single-tap RF SIC circuitry as clear from Fig. 1. A single-tap SIC circuit provides very narrow cancellation bandwidth, however, using such SIC circuit with antenna proposed in this work provides very high amount of SIC for 20MHz bandwidth at RF front end compared to previous works [4-5].

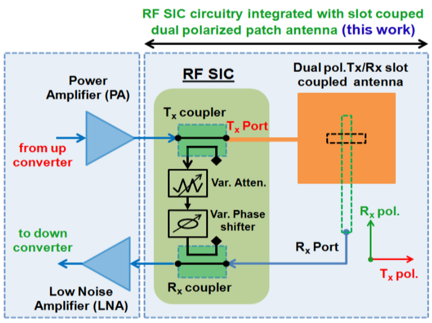

Fig. 1. *Block diagram of SIC-integrated slot coupled patch antenna to achieve 80dB Tx-Rx interport RF isolation for 20MHz band width.*

Monostatic Antenna Module with Integrated SIC Circuitry: As shown in Fig. 2, proposed antenna module deploys λ/4 microstrip feed to excite radiating element for T_x mode while slot coupled feeding has been used for R_x operation. Such hybrid feeding provides improved interport isolation for IBFD antenna as compared to patch with symmetrical feeding at both ports [6]. Firstly, polarization diversity reduces T_x-R_x coupling and additional interport isolation is achieved through single-tap RF SIC circuitry. The cancellation signal is produced by directional couplers, voltage controlled, surface mount phase shifter and attenuator. As shown in Fig. 2, antenna resonates at same T_x and R_x frequencies with dual polarization characteristics when radiating patch is excited from two perpendicular ports. Port 1 and Port 2 are designated for T_x with linear horizontal polarization and R_x with linear vertical polarization modes respectively as indicated in Fig. 2.

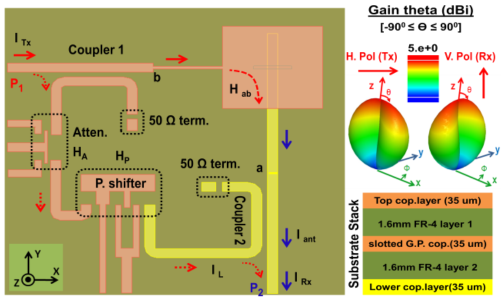

Fig. 2. *EM Model for antenna module with integrated RF SIC (designed using two layered FR-4 substrate with ε_r = 4.4 & tanδ =.02).*

Mathematical description for RF SIC proposed antenna module can be established through very simple analysis. For simplicity, assume that $S_{11} = S_{22} = 0$, then total current flowing out of port 2 ($\boldsymbol{I}_{\mathbf{Rx}}$) is given by:

$$I_{\mathrm{Rx}} = T_2 I_{\mathrm{ant}} + C_2 I_{\mathrm{L}} \quad (1)$$

where $\boldsymbol{I}_{\mathrm{ant}}$ (current flowing through patch) and $\boldsymbol{I}_{\mathrm{L}}$ (loop current) are related to $\boldsymbol{I}_{\mathrm{Tx}}$ (current flowing in to T_x port-P_1) as:

$$I_{\mathrm{ant}} = I_{\mathrm{Tx}} T_1 H_{\mathrm{ab}} \quad (2)$$

$$I_{\mathrm{L}} = I_{\mathrm{Tx}} C_1 H_{\mathrm{A}} H_{\mathrm{P}} \quad (3)$$

Using (2) and (3), eq.(1) can be written as:

$$I_{\mathrm{Rx}} = T_2 I_{\mathrm{Tx}} T_1 H_{\mathrm{ab}} + C_2 I_{\mathrm{Tx}} C_1 H_{\mathrm{A}} H_{\mathrm{P}} \quad (4)$$

The couplers at T_x and R_x ports are symmetrical so:

$$C_1 = C_2 = C \text{ and } T_1 = T_2 = T \quad (5)$$

The current coupling ratio for T_x and R_x ports is given by:

$$\frac{I_{Rx}}{I_{Tx}} = T^2 H_{\mathrm{ab}} + C^2 H_{\mathrm{A}} H_{\mathrm{P}} \quad (6)$$

where *C*, *T* denote current coupling and transmission coefficients for couplers while H_{ab}, H_A and H_P represent current transmission co-efficient for patch, variable attenuator and phase shifter respectively.

Each directional coupler provides 90° phase shift at through port as both couplers are designed by using λ/4 long coupled transmission lines. The current coupling ratio given by (6) should be equal to zero for perfectly decoupled T_x-R_x ports:

$$H_{\mathrm{ab}} = C^2 H_{\mathrm{A}} H_{\mathrm{P}} \quad \text{for } |\mathrm{T}| \cong 1 \text{ and } \angle \mathrm{T} = 90^o \quad (7)$$

Eq.(7) states that transfer function for currents flowing through RF SIC loop and radiating element should be same in order to cancel the SI at R_x port to perfectly decouple it from T_x port. The required SIC condition stated by eq. (7) can be defined in terms of RF power [dB] as:

$$2 * [L_{\mathrm{d}}] + [S_{\mathrm{ab}}] = 2 * [C_{\mathrm{d}}] + L_{\mathrm{A}} + L_{\mathrm{P}} \quad (8)$$

$$\theta_{\mathrm{ab}} = \theta_{\mathrm{A}} + \theta_{\mathrm{p}} \quad (9)$$

where L_d, C_d represent insertion loss and coupling for couplers while L_A, L_P, Θ_A, Θ_A, denote attenuation, insertion loss and phase variations for attenuator and phase shifter respectively. The isolation and phase characteristics for patch are represented by S_{ab} & Θ_{ab} respectively.

Experimental Results for Implemented Antenna Module: The compact monostatic antenna module with integrated single-tap RF SIC was implemented on double layered FR4 substrate (ε_r = 4.4, tanδ =.02 and thickness (h) = 1.6 mm for each layer) as shown in Fig. 3. The dimensions of implemented antenna module and designated T_x and R_x ports are also shown in Fig. 3. As indicated in Fig. 3, two directional couplers with 15 dB coupling were used at Port 1 and Port 2 to sample the T_x signal and subtract it from R_x port respectively. The sampled T_x signal is processed through voltage controlled, surface mount attenuator and phase shifter in order to achieve required characteristics for this cancellation signal as discussed earlier. We have used EVA-3000+ and JSPHS-2484+ from Mini-circuits as surface mount attenuator and phase shifter, respectively. The attenuator provides typical attenuation changes from 24 dB to 3.5 dB and the phase shifter has 0°-180° phase variations with 0-8 Vdc and 0-15Vdc tuning voltages respectively.

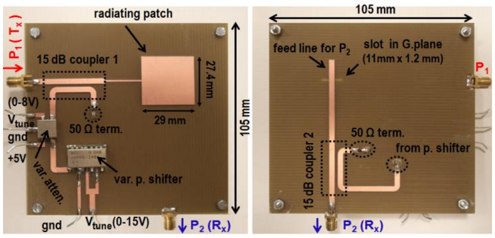

Fig. 3. *Implemented compact antenna module with integrated single tap-RF SIC (implemented on FR-4 substrate with ε_r = 4.4 & tanδ =.02).*

The implemented antenna module was measured in lab environment in the presence of SI resulted by RF reflections from nearby objects. Such environmental reflections greatly affect the interport isolation performance of antenna; however, our antenna is capable to cancel this type of SI with the help of tunable RF SIC circuit. The SIC circuit was tuned to meet the SIC conditions stated in (8) and (9). As reported in [6] and shown in Fig. 4, polarization diversity with hybrid feeding provides $S_{ab} \approx$ 60 dB. Hence, loop attenuator and phase shifters are tuned to L_A= 25dB, Θ_p = 165° along with C_d = 15dB and $L_p \approx$ 3dB. The measured S_{11}, S_{22} and inter-port isolation results for implemented antenna module are shown in Fig. 4. Measured 10 dB-return loss bandwidth is around 60 MHz (2.44 GHz to 2.50 GHz) and peak interport isolation is better than 97 dB. Implemented antenna achieves around 80dB interport isolation for 20MHz bandwidth (2.46GHz to 2.48GHz) as clear from Fig. 4.

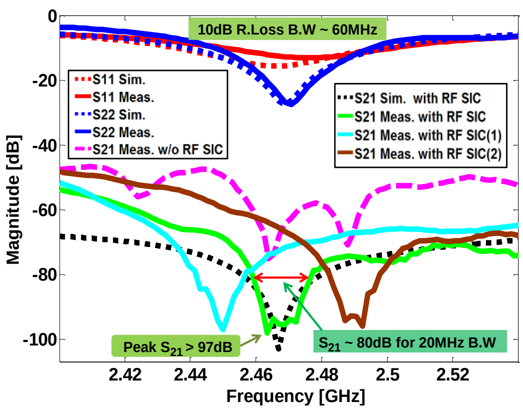

Fig. 4. *Simulated and measured port matching and Tx-Rx interport isolation results for antenna module with integrated SIC circuit.*

Moreover, for implemented antenna module, the 20MHz bandwidth with 80 dB SIC can be tuned with in antenna's 10 dB return loss impedance bandwidth of 60 MHz with the help of RF SIC circuit. For instance, two cases are shown in Fig. 4, where 20 MHz SIC bandwidths with around 80 dB interport isolation have been achieved for 2.44GHz-2.46 GHz and 2.48GHz-2.5GHz frequencies respectively.

Measured E-plane co-polarization and cross polarization gain patterns for implemented antenna module are shown in Fig. 5. Antenna module provides around 4.5 dBi gain for each port excitation with 80° half power beam width (HPBW). Measured cross-polarization levels for both T_x and R_x ports are almost 35dB down from respective co-polarization components on bore-sight in E-plane as clear from Fig. 5.

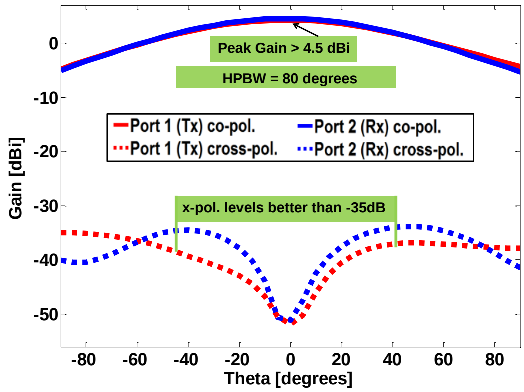

Fig. 5. *Measured co-polarization and cross polarization E-plane gain patterns at 2.47GHz for dual polarized antenna with integrated RF SIC.*

Conclusion: In this letter, a compact (105mm x 105mm) monostatic antenna module has been presented for single channel full duplex wireless applications. Implemented antenna module with small form factor having around 80dB T_x-R_x isolation within 20 MHz bandwidth can be used to implement a compact 2.4/2.5 GHz IBFD transceiver. The integrated RF SIC circuitry is capable to tune the 80 dB cancellation bandwidth of 20MHz with in 60MHz.

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H. Nawaz, Ö. Gürbüz (*Electronics Engineering, Sabanci University, Istanbul, Turkey).* I.Tekin (Electronics Engineering and SUNUM-Nanotechnology Research Center, Sabanci University).
E-mail: hnawaz@sabanciuniv.edu

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