60-GHz CONTACTLESS CONNECTIVITY: FULL-DUPLEX AND TRANSMISSION THROUGH VARIOUS MEDIA

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Executive Summary
In the field of smart connectivity, the use of the 60-GHz technology attracts attention not only in Industrial but also other BU’s. An advanced 60-GHz antenna technique to realize a full-duplex data link is proposed. The feasibility to perform data transmission through different media, e.g. concrete, oil, water, and plastic, is investigated, and the solution using a matching layer is proposed. This proposal for contactless connectivity will open more possibilities for TE addressing typical customer applications that have to operate, for instance, in a harsh environment.

Keywords: Smart Connectivity, Wideband Antenna, 60 GHz, Full Duplex, Circular Polarization, Propagation Medium

I. Problem Statement

In the current contactless connector ARISO product (see Fig. 1), there is a need for having a higher data rate beyond 1 Gbps [1]. The obvious way to support this speed is by moving the frequency of the transceiver towards the 60-GHz Industrial, Scientific, and Medical (ISM) frequency band.

Given the large amount of available bandwidth at this frequency (i.e. 7 – 9 GHz), a simple modulation technique can already accommodate a high-speed data communication with low implementation complexity. The use of the simple modulation also assures that the system is less prone to error, so no further baseband processing, such as error correction, is required. In addition to that, this less baseband processing also means a low end-to-end latency, which is the requirement for industrial applications.

As can be seen in Fig. 1, the industrial applications are often associated with a rotating machinery such as robotic arm for milling and centrifuging. In other words, rotational freedom has to be supported during the data communication. This feature can be realized by using an antenna with radiation of circular polarization. Furthermore, often for industrial application, various propagation media are present and need to be supported by the data communication system [1]. This medium can be either concrete, oil (e.g. in robotic arm), water, or plastic. In this paper, an approach using a matching layer to allow the 60-GHz wave propagation through these media will be discussed.

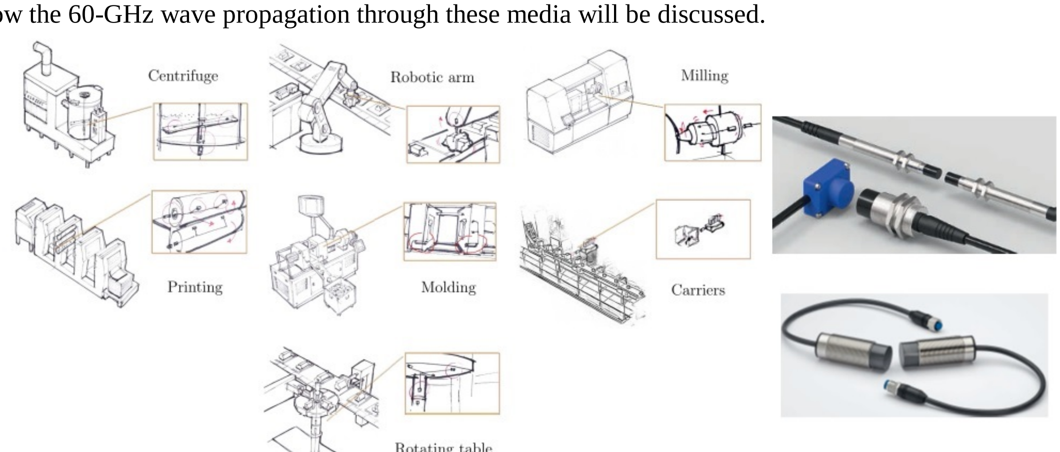

Fig. 1. Industrial applications and contactless ARISO product (M12 and M30) [2].

Furthermore, bi-directional communication is one of the important requirement for a smart connectivity. One way to provide bi-directionality is by using Frequency-Division Duplex (FDD), which is a full-duplex operation mode. FDD implies that we cannot use the entire available bandwidth. Few frequency channels are dedicated for transmission, while other channels are for reception. Another common concept for providing bi-directionality is Time-Division Duplex (TDD). TDD does not lend itself to data transmission that fulfills the requirement for a low latency. The reason is that the transmission and reception do not occur simultaneously. One operation mode needs to wait until another mode finishes (or half-duplex). In this paper a full-duplex solution where all the frequency channels can be used for both transmit and receive simultaneously will be proposed, and its performance is characterized.

In order to support those said requirements, an advanced antenna system needs to be developed. The transmitter-receiver (Tx-Rx) isolation of such an antenna system needs to be enhanced in order to eliminate the crosstalk, which will be discussed in Section II.A & B. It will also be shown that the signal-to-noise ratio (*SNR*) is not the limiting factor here (due to the short communication distance), but signal-to-interference ratio (*SIR*).

II. METHODS AND RESULTS

A. Self-Interference (Crosstalk) and Antenna Isolation

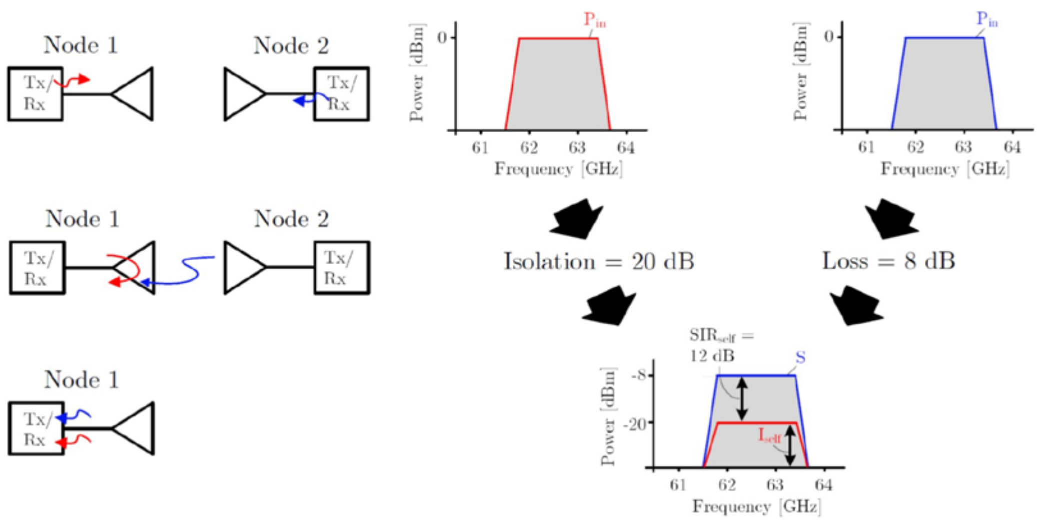

Fig. 2. Illustration of the received signal *S* (in blue) and self-interference power I_{self} (in red) for a frequency channel. The transmitted power P_{in} (=0 dBm) could be arbitrary and will lead to the same signal-to-interference ratio, $\mathrm{SIR}_{\mathrm{self}}$.

As described in the previous section, full-duplex system is needed, and it implies that both Tx and Rx functionalities of the chip will operate simultaneously. Hence, it is important to analyze the influence of the interference at the Rx side (i.e. victim). The source of this interference can be from internal, such as near-end crosstalk (NEXT) from the local Tx, and external aggressor. Issues occurring at the receiver due to the interference are, a.o., desensitization and reduced signal-to-interference ratio *SIR*. The desensitization is the reduction of the amplifier's sensitivity where the low noise amplifier (LNA) is saturated due to the large incoming signal. Interference mitigation is required in order to reduce BER for a given desired signal power.

An illustration to describe this situation is shown in Fig. 2. The self-interference power I_{self} (or NEXT) has to be suppressed as much as possible in order to improve "the signal-to-interference ratio due to the self-interference" or SIR_{self}. In addition to that, in this contactless connector where the use is for both directions, how much PA power is applied will not help the resulting signal-to-interference ratio SIR_{self} at the remote Rx if both communication directions are intended to perform equally. Therefore, the important factor here is that the isolation between the Tx and Rx ports has to be maximized.

Also in Fig. 2, an example of the communication system with a 20-dB Tx-Rx isolation and 8-dB transmission loss leaves a SIR_{self} = 12 dB (= isolation - transmission loss) for Rx at Node 1 to detect the received signal with a specific sensitivity requirement. Based on the theoretical bit error rate (BER) of quadrature phase-shift keying (QPSK) modulation, this 12-dB SIR_{self} can support a signal detection with BER = 10^{-8}. The antenna system with a larger isolation (e.g. 30 dB), whenever it is possible, is preferred. In this work, the minimum required isolation is 20 dB. In the next section, an antenna system with a large and wideband Tx-Rx port isolation is proposed and characterized.

B. Design of Full-Duplex Antenna with Wideband Isolation

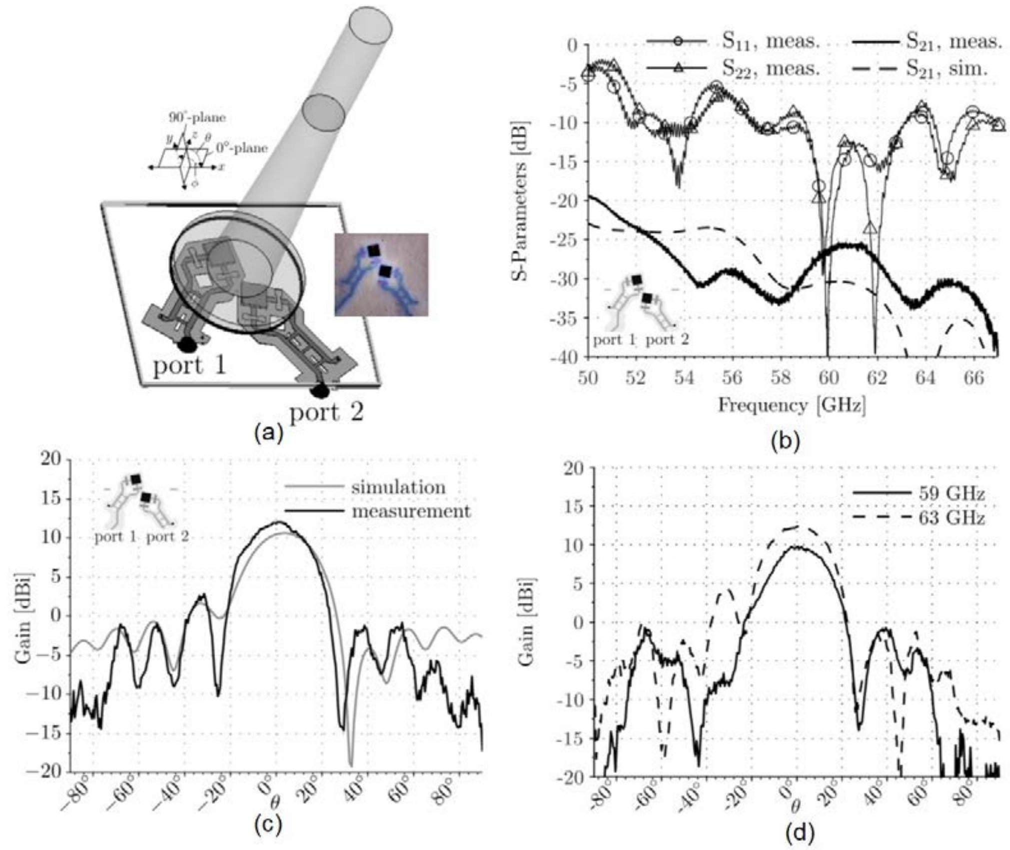

Fig. 3. (a) Antenna structure, (b) simulated (using CST MWS Studio) & measured S-parameters, (c) simulated & measured (RHCP) radiation pattern in the 0-plane at 61 GHz, and (d) at 59 & 63 GHz.

In addition to the high Tx-Rx port isolation, an antenna system that supports full-duplex operation and circular polarization is proposed and reported. The orientation of circular polarization (either right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP)) is employed to realize an uplink (e.g. using RHCP) and downlink (LHCP) channel for full-duplex communication at the same operating frequency.

Fig. 3(a) shows the structure of the proposed antenna system which consists of branch-line couplers, patch antennas, and a dielectric rod. The coupler is used for generating the excitation of circular polarization (port 1: LHCP, port 2: RHCP operation). The patch antennas couple the electromagnetic (EM) power to the dielectric rod. This rod provides a high gain/directivity of the antenna system for given limited space in M12 connector housing (as demonstrated in our initial design in [3]). Note that the coupler and patch radiators are realized on a multilayered substrate carrier, and the material of this carrier is liquid crystal polymer (LCP).

For the patch antenna, novel stacked patches with parasitic elements and cascaded couplers with a defected ground structure (DGS) are here proposed to achieve a wideband performance. Furthermore, angular and lateral offsets of the patch position are incorporated in order to improve the isolation between the patch antennas. The optimization based on the phase cancellation for each patch's excitation path has been performed. In this way, spacing between the antennas can be reduced while still maintaining sufficient isolation. The spacing needs to be reduced, because each antenna element should still maintain a high coupling efficiency of the EM power to a common rod.

Scattering parameters (S-parameters) of this antenna system are presented. The thru-reflect-line (TRL) calibration technique is performed to have an accurate measurement result. In Fig. 3(b), the measured return loss ($|S_{11}|$) and Tx-Rx isolation ($|S_{21}|$) are better than 10 dB and 25 dB, respectively, for a large bandwidth. In Fig 3(c) & (d), the radiation pattern for different frequencies is reported. A satisfactory agreement between the simulation and measurement is observed. The resulting maximum gain is 12.4 dBi (at 63 GHz).

C. Demonstration: Transmission from Rod Antenna to Rod Antenna

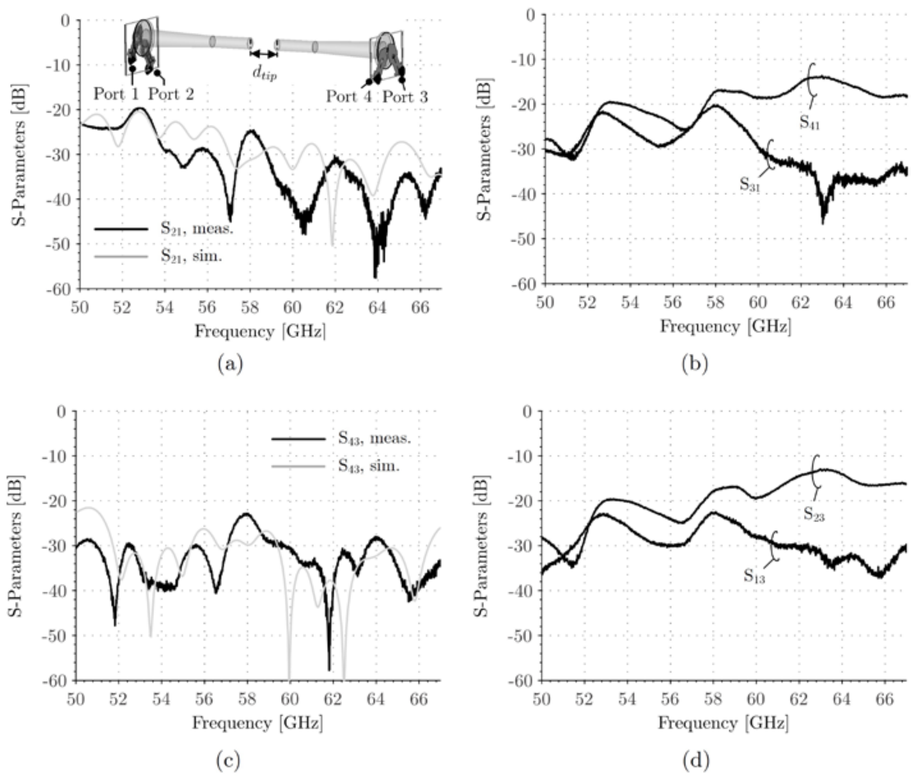

Fig. 4. Measured and simulated S-parameters of the antenna pair for d_{tip} = 5 mm.

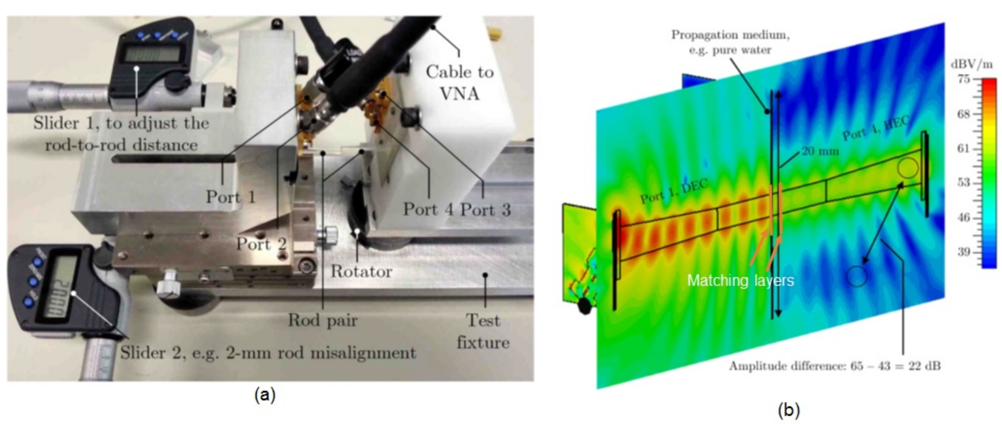

Fig. 5. (a) Measurement setup for rod-to-rod transmission. (b) E-field animation for 60-GHz propagation through water with medium thickness t_{med} = 0.1 mm.

The implementation of the 60-GHz antenna for contactless-connector applications will be tested, and the results will be reported in this section. A fixture (see Fig. 5(a)) is designed for performing this end-to-end measurement. This fixture also allows to do the measurement under various conditions, i.e. range, misalignment, rotation, and yaw (or tilt) of the contactless-connector antenna.

The measured performance is reported in Fig. 4 for the case of antenna distance d_{tip} = 5 mm (tip-to-tip distance). The simulated and measured isolation (or NEXT) is shown for both paired antennas. The transmission coefficient and far-end crosstalk (FEXT) are also given. As can be seen, the transmission coefficient and isolation are around -18 dB and 30 dB in the 60-GHz ISM frequency band. Moreover, because of high polarization purity of the antenna, a good FEXT relative to transmission coefficient is obtained.

III. DISCUSSION AND KEY POINTS

A. Influence of Propagation Medium

Introducing a dielectric medium between the contactless connectors will not only influence the EM-wave transmission between the local and remote antennas (see animation in Fig. 5(b)) but also will cause more reflections which degrade the isolation performance of the local antenna system. The latter can be explained by the fact that the reflected wave will change its orientation of circular polarization. This propagation medium can be concrete, oil, water, or plastic, and, as a result, multiple reflections inside and outside this medium are unavoidable. To minimize the performance degradation due to this medium, a matching layer is required, that can be placed at the tip of the dielectric rod (i.e. the connector's cap). A model to analyze and optimize the performance by varying the matching layer's thickness t_{match} and permittivity is shown in Fig. 6. A detailed analysis of this model is discussed in [4].

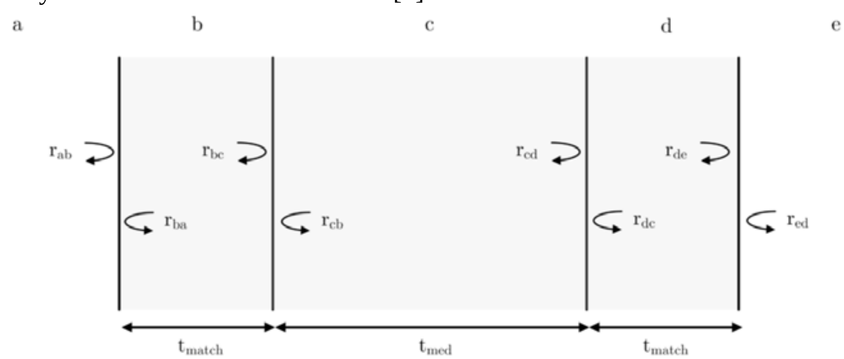

Fig. 6. Model of three-layered dielectric structure including the corresponding reflection coefficients (r_{nm}) from medium *m* to medium *n*.

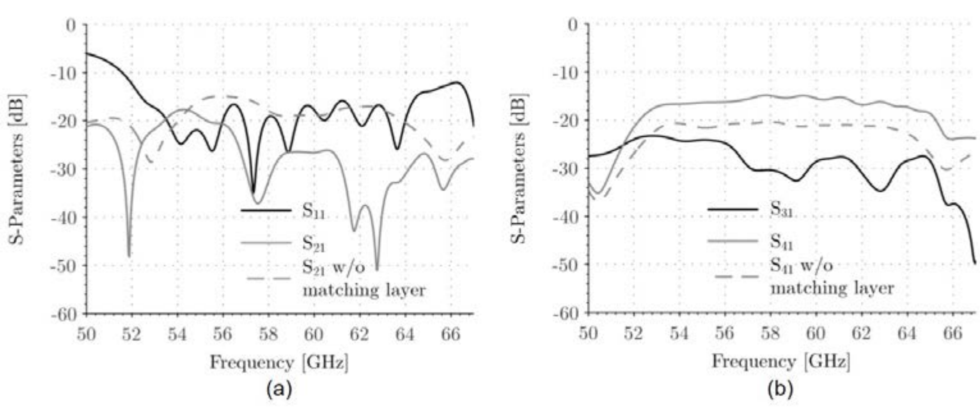

Fig. 7. Simulated S-parameters for the case of propagation through water with matching layer. (a) Reflection coefficient and NEXT and (b) transmission coefficient and FEXT. It can be seen that the Rx sensitivity is not the limiting factor here.

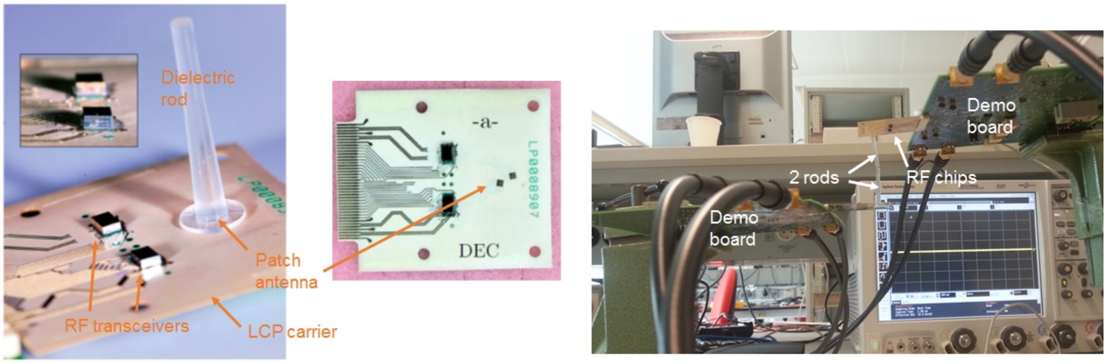

Fig. 8. Rod antenna with assembled 60-GHz transceivers (from NXP) and the demo setup.

For a water thickness of 0.1 mm, the isolation (|S_{21}|) and transmission coefficient (S_{41}) for the case of with and without the matching layer are reported in Fig. 7. For full-duplex communication in a common frequency channel, it is necessary to have a sufficient *SIR*. As can be observed, the isolation is dramatically reduced if no matching layer is used, yet the transmission coefficient is only slightly reduced. Using an optimized matching material (t_{match} = 1 mm and ε_r = 9), *SIR* is now at least 12 dB. This *SIR* can ensure a data transmission with QPSK modulation (BER = 10^{-8}) for frequencies 57 - 66 GHz. For a thicker water medium (0.5 and 1 mm), a separate frequency channel is needed due to the limited *SIR* (= -5 and -20 dB, respectively). For other media, such as cement concrete and glass, the obtained *SIR* (best-case for the whole bandwidth) using the matching layer is 10 dB and 9 dB, respectively.

For propagation media with a lower permittivity, such as plastic (e.g. Polystyrene) and oil, no matching layer is required, and the obtained *SIR* is 10 dB and 17 dB, respectively. Finally, it can be concluded that, albeit various propagation media, the use of the matching layer improves the link performance, namely by enabling full-duplex while using a common antenna (thus, a small form factor) and allowing a higher data speed. This opens more possibilities for TE addressing customer contactless-connectivity applications that have to operate, for example, immersed in oil or water.

B. Demonstration Using Active RF Transceivers

The integration of the antennas system with 60-GHz transceivers on a flex LCP carrier (module board) is performed by means of flip-chip technology (see Fig. 8). Currently, the process iteration for flip-chipping on a flex is still on-going. In addition to that, the demonstration board for data acquisition and power regulation is designed and connected to the module board.

IV. CONCLUSIONS

In this paper, the critical issues for a transparent data link based on 60-GHz technology are addressed:

- Bi-directional transmission using full-duplex mode of operation is realized using two adjacent patches exciting a common rod. A tremendous isolation improvement in terms of magnitude and bandwidth has been shown.
- Solution for a reliable transmission through various propagation media is proposed, namely by using matching layer. Because of limited *SIR*, separate frequency channels for transmit and receive are recommended.

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