St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2022 Vol. 15, No. 3.3
Научно-технические ведомости СПбГПУ. Физико-математические науки. 15 (3.3) 2022

Conference materials
UDC 52-77
DOI: https://doi.org/10.18721/JPM.153.368

Millimeter wave photonic crystal waveguides fabricated via direct machining

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Abstract. At the moment, millimeter waves attract close attention not only of the scientific community, but also of the communication industry. Number of studies worldwide are currently focused on finding efficient solutions for the transceiver technologies compatible with beamforming and carrier frequencies beyond 100 GHz. It was recently demonstrated that the technology of integrated silicon photonic crystals provides decent propagation loss and low fabrication complexity upon implementation of waveguide components for the sub-mmWave band. In this paper, we report on the millimeter wave photonic crystal waveguides fabricated from high permittivity PCB laminate by the means of direct machining. Inspection of the fabricated waveguide samples reveals no violation of the photonic crystal geometry due to the fabrication tolerances. The photonic crystals are designed for operation at frequencies 140–160 GHz, and we measure the power attenuation coefficient attributed to the waveguide geometry of 0.02 dB/mm at 145 GHz. The design considerations, including justification of the laminate choice, and detailed results of performance tests are presented in the paper.

Keywords: millimeter waves, photonic crystal waveguide, high permittivity PCB laminate, direct machining, 2D CNC machining

Funding: Support from the Basic Research Program of the National Research University Higher School of Economics in the development of experimental setup and methods is gratefully acknowledged. Experimental samples were fabricated under the support of the Russian Science Foundation grant No. 21-72-10119, https://rscf.ru/project/21-72-10119/.

Citation: Prikhodko A. N., Belikov I. I., Lvov A. V., Shurakov A. S., Goltsman G. N., Millimeter wave photonic crystal waveguides fabricated via direct machining. St. Petersburg State Polytechnical University Journal. Physics and Mathematics, 15 (3.3) (2022) 345–349. DOI: https://doi.org/10.18721/JPM.153.368

Материалы конференции
УДК 52-77
DOI: https://doi.org/10.18721/JPM.153.368

Фотонно-кристаллический волновод миллиметрового диапазона, изготовленный методом механической обработки

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Аннотация. В настоящий момент миллиметровый волновой диапазон привлекает внимание не только научного сообщества, но и отрасли связи. Большое число исследований по всему миру сосредоточено на поиске эффективных решений для технологий приемопередатчиков, совместимых с функцией управления пучком при несущих частотах выше 100 ГГц. Недавно было показано, что технология интегрированных кремниевых фотонных кристаллов обеспечивает простоту изготовления и низкие вносимые потери при создании волноводных компонентов субмиллиметрового диапазона. В данной статье мы сообщаем о фотонно-кристаллических волноводах миллиметрового диапазона, изготовленных методом механической обработки из ламината для печатных плат с высокой диэлектрической проницаемостью. При контроле качества изготовленных образцов волноводов не выявлено нарушения заданной геметрии фотонного кристалла вследствие погрешности изготовления. Фотонные кристаллы спроектированы для использования в полосе частот 140–160 ГГц: измеренное на частоте 145 ГГц значение коэффициента ослабления мощности, связанного с геометрией волновода, составило 0.02 дБ/мм. Подробные результаты измерений технических характеристик, а также ключевые аспекты проектирования, включая обоснование выбора ламината, представлены далее в тексте статьи.

Ключевые слова: миллиметровые волны, фотонно-кристаллический волновод, ламинат для печатных плат с высокой диэлектрической проницаемостью, механическая обработка, 2D ЧПУ обработка

Финансирование: Выражается благодарность Программе фундаментальных исследований НИУ ВШЭ за поддержку в разработке экспериментальной установки и методик. Экспериментальные образцы изготовлены при поддержке гранта Российского научного фонда № 21-72-10119, https://rscf.ru/project/21-72-10119/.

Ссылка при цитировании: Приходько А. Н., Беликов И. И., Львов А. В., Шураков А. С., Гольцман Г. Н. Фотонно-кристаллический волновод миллиметрового диапазона, изготовленный методом механической обработки // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2022. Т. 15. № 3.3. С. 345–349. DOI: https://doi.org/10.18721/JPM.153.368

Introduction

At the moment, the millimeter wave (mmWave) band attracts close attention not only of the scientific community, but also of the communication industry. Progress in a mmWave communication is in line with the society needs for the speed and quality of data transfer which drastically enlarged in the coronavirus pandemic era. Next generation communication networks should rely on the transceiver technologies compatible with beamforming and carrier frequencies beyond 100 GHz [1]. This may potentially result in a fatal increase of their complexity, fabrication and operational costs. Thus, number of studies worldwide are currently focused on finding efficient software and hardware solutions.

It was recently proposed that the technology of integrated silicon photonic crystals is beneficial compared to that of conventional hollow metallic rectangular waveguides at sub-millimeter waves [2]. The benefits are mainly related to the reduction of propagation loss and fabrication complexity upon implementation of a single-mode waveguide and simple passive components. In this paper, we report on the technology of a mmWave photonic crystal waveguide (PCWG) fabricated by the means of direct machining. PCWG utilizes high permittivity laminate [3]. The geometry of photonic crystal is implemented with the aid of a PCB prototyping machine [4]. Metallization on both sides of the laminate is removed via wet etching at the final step of the fabrication process. The waveguide is designed for a single-mode operation at frequencies 140–160 GHz. The design considerations and results of performance tests are presented further in the text.

Evaluation of Fabricated Samples

Our designs make use of FSD1020T series laminate, which attributes relative permittivity (ε_r) of 10.2 and loss tangent (tanδ) of 0.002 at 10 GHz according to the manufacturer specifications.

Suitability of the laminate for our task is justified by evaluation of its dielectric properties in the mmWave band. This is achieved by measuring return (*RL*) and insertion losses (*IL*) of a WR6.5 rectangular waveguide section with an FSD1020T insert installed in it. The lengths of the waveguide section (l_{ws}) and the dielectric insert (l_{di}) are 25 and 6.4 mm, respectively; other their linear dimensions are identical. During the return loss measurement, we use a solid state mmWave source providing up to 120 mW of output power over the frequency range from 133 to 162 GHz. The source and the waveguide under study are connected through a waveguide directional coupler with a coupling factor of -15 dB and an isolation of 30 dB. The dielectric insert inside the waveguide is placed next to its flange facing the directional coupler, i.e., the front flange. For a given frequency of the source (F_{ss}), the *RL* value is calculated with the aid of equation 1.

$$RL = 10\log_{10}\left(P_1 P_2^{-1}\right), \tag{1}$$

where P_1 and P_2 are the mmWave powers at the input and transmitted ports of the directional coupler, respectively. The power values are consequently measured by a precision waveguide power meter while the source is permanently connected to the coupled port of the directional coupler. During the insertion loss measurement, the source is disconnected from the latter port and is attached to the rear flange of the waveguide under study. This is to keep electric length of the transmission line constant which is useful in further analysis of the measured frequency profiles. At given F_{ss}, the *IL* value is defined by ratio of power provided by the source (P_{ss}) to that measured by the power meter (P_{pm}) in accordance with equation 2. Results of both the return and insertion loss measurements are provided in Fig. 1.

$$IL = 10\log_{10}\left(P_{ss} P_{pm}^{-1}\right). \tag{2}$$

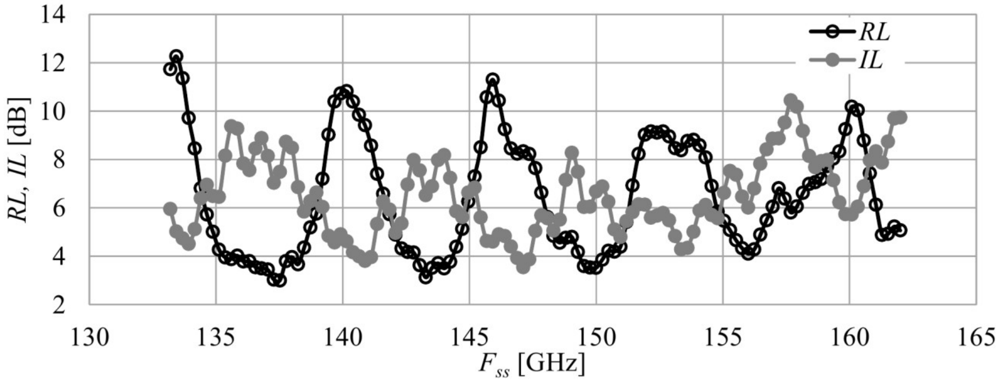

Fig. 1. Return and insertion losses measured for a WR6.5 rectangular waveguide section with an FSD1020T insert installed in it

Measured frequency profiles of the return and insertion losses are used to evaluate dielectric properties of the FSD1020T insert. This is achieved with the aid of math provided in equations 3–5 accompanied by S-parameter simulations for the studied transmission lines in QUCS [5]. Degree of agreement between the measured and simulated frequency profiles is used as a feedback parameter. In the end, we obtain $\varepsilon_r \approx 10.6$ and $\tan\delta = 0.011$ at 145 GHz. This corresponds to the laminate power attenuation coefficient (α) of 0.47 dB/mm. These values are used to develop geometry of the photonic crystal intended for the implementation of a single-mode waveguide.

$$A = 1 - 10^{-0.1RL} - 10^{-0.1IL}, \tag{3}$$

$$\tan\delta = -\ln(A)c(2\pi F_{ss}\varepsilon_r^{0.5} l_{di})^{-1}, \tag{4}$$

$$\alpha = -10\log_{10}(A) l_{di}^{-1}. \tag{5}$$

Here A is the absorptance and c is the speed of light in vacuum.

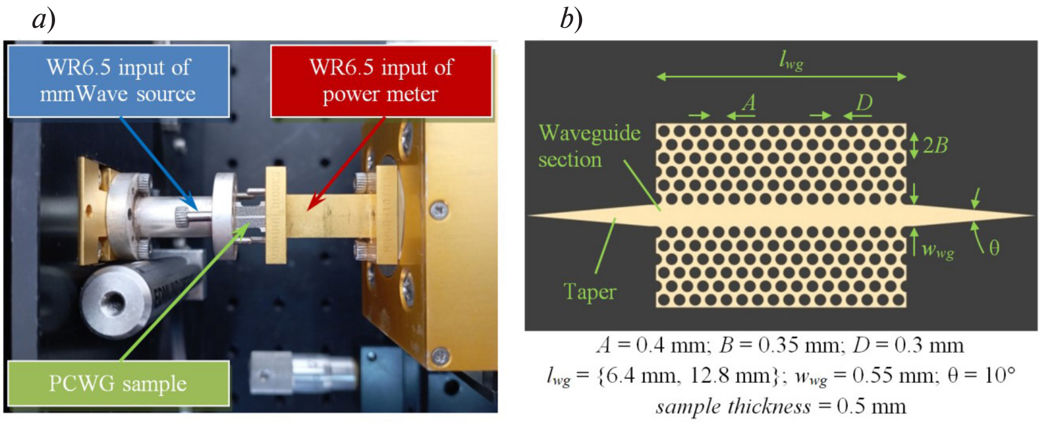

Fig. 2. Measurement setup with a PCWG sample installed (*a*); (*b*) geometry of the samples (*b*)

We fabricate PCWG samples with waveguide sections of several lengths (l_{wg}) to evaluate insertion losses due to the energy leakage into a free space (L_{wg}) and those due to the input/output coupling elements (L_{ce}). Thus, total insertion loss (L_{tot}) can be explicitly presented as a function of lwg as $L_{tot}(l_{wg}) = 2L_{ce} + (\alpha + \alpha_{wg})$ lwg if measured in decibels. Here $\alpha_{wg} = L_{wg}\ l_{wg\text{-}1}$ is the power attenuation coefficient attributed to the waveguide geometry.

Fig. 2, *a* provides photo of the fabricated PCWG sample installed between WR6.5 inputs of a solid state mmWave source and precision power meter. Referring to Fig. 2, *b*, PCWG section is integrated with input/output tappers, which ensure coupling with the TE10 mode when inserted into a WR6.5 waveguide. Positioning of the sample together with the power meter with respect to the mmWave source is maintained with the aid of a precision 3D translation stage.

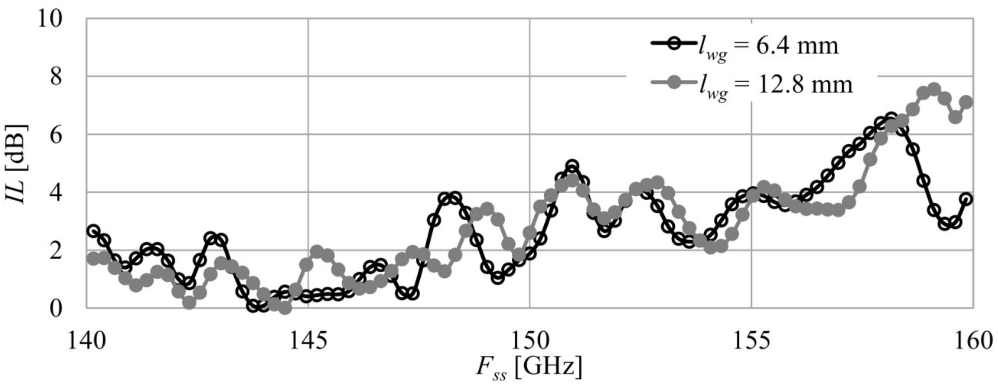

Fig. 3. Insertion losses of the fabricated PCWG samples (dielectric losses are calibrated out)

We measure $\alpha_{wg} = 0.02$ dB/mm and $L_{ce} = 0.2$ dB at 145 GHz. Detailed inspection of the fabricated PCWG samples reveals no violation of the photonic crystal geometry due to the fabrication tolerances. As provided in Fig. 3, frequency profiles of the samples insertion losses agree well, once absorption and scattering in FSD1020T are calibrated out. All together proves suitability of a 2D CNC machining for implementation of mmWave PCWG components.

Conclusion

In this paper, we report on the development and fabrication of a mmWave PCWG making use of an FSD1020T series PCB laminate. Dielectric properties of the laminate were preliminary evaluated by measuring reflection and transmission spectra of a WR6.5 rectangular waveguide section with a dielectric insert made of it. We measured $\varepsilon_r \approx 10.6$ and $\tan\delta = 0.011$ at 145 GHz compared to those of 10.2 and 0.002 specified by the manufacturer at 10 GHz, respectively. The measured values were used to develop geometry of the photonic crystal intended for the implementation of a single-mode waveguide. Study of the PCWG samples fabricated via 2D CNC machining revealed power attenuation coefficient of 0.02 dB/mm attributed to the waveguide geometry. Frequency profiles of the samples insertion losses agreed well, and we observed no violation of the developed geometry upon fabrication. All together proves suitability of a 2D direct machining, i.e., drilling and milling, for implementation of mmWave PCWG components.

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Received 15.08.2022. Approved after reviewing 15.08.2022. Accepted 05.09.2022.