Saratov State University | *V.A. Kotel'nikov Institute of Radio Engineering and Electronics RAS* | *Laser Center LLC* | *Yuri Gagarin State Technical University of Saratov*

FEATURES OF NANOSECONDS AND PICOSECONDS LASER ABLATION FOR MICROFABRICATION OF PLANAR SLOW-WAVE STRUCTURES FOR MILLIMETER-BAND LOW-VOLTAGE TUBES WITH SHEET ELECTRON BEAM

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Agenda

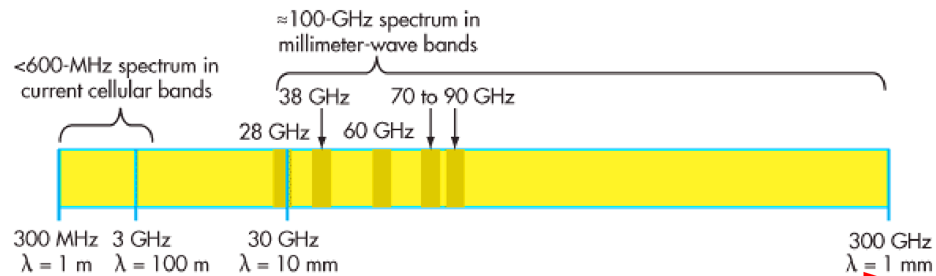
- Actuality
- Background and microfabrication technologies
- Our original approach to microfabrication, equipment for microfabrication and study
- Microfabricaton by long (nanosecond) pulses laser ablation
- Microfabricaton by short (picosecond) pulses laser ablation
- Conclusions and our plans on the future work…

Actuality

Vacuum Electronic Devices (TWT, BWO, klystron, etc.)

MAIN TRENDS

Moving to the millimeter and sub-millimeter bands



Miniaturization

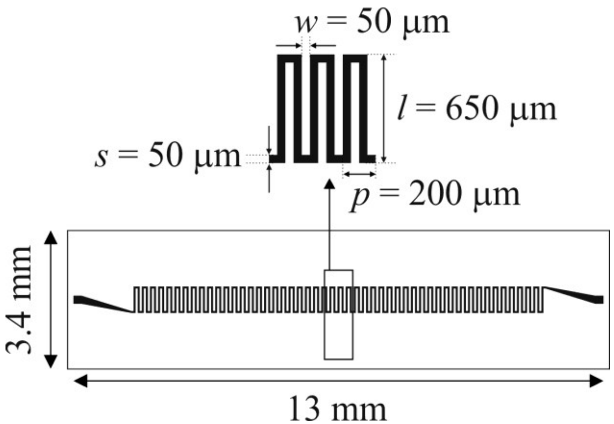
High frequency travelling wave (TWT) tube amplifiers

- **For increasing operating frequencies the slow wave structure (SWS) dimensions decrease**
- **Helix based TWTs are limited up to around 60 GHz (few hundred of microns diameter)**
- **New architectures and new fabrication techniques are necessary**
- **Planar slow-wave structures enable efficient fabrication and tube assembly**

Planar slow wave structures. Background and modifications

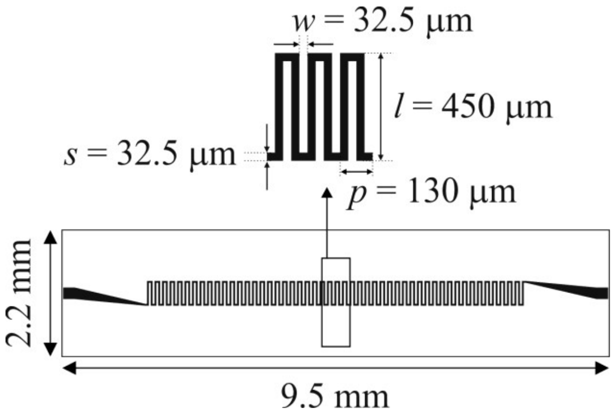
•**1990-1995.** Y.V. Gulyaev, N.I. Sinitsyn, G.V. Torgashov, et al., IRE RAS, Saratov. Planar SWS for microminiaturized vacuum electron devices;
•**2009.** S. Sengele, H. Jiang, J.H. Booske, C.L. Kory, D. van der Weide, R.L. Ives. University of Wisconsine-Madison & Calabazas Creek Research, USA. Selectively metallized on top silicon meander SWS for W-band TWT;
•**2012.** F. Shen *et al.*, National Key Laboratory of Science and Technology on Vacuum Electronics, University of Electronic Science and Technology of China, Chengdu. V-shape meander-line 140 GHz TWT for low-voltage (5 kV) operation;
•**2013.** S-shaped planar meander slow wave system on dielectric substrate. Ningfeng Bai, Leilei Gu, Changshen Shen, Jinjun Feng, Fujiang Liao, Xiaohan Sun. Proceedings of the 14th IEEE International Vacuum Electronic Conference (IVEC-2013), Paris, France; DOI: 10.1109/IVEC.2013.6571098;
•**2014.** Planar wire array SWS for better mode control in a sheet-beam device . L.B. Nguyen, T.M. Antonsen, and G.S. Nusinovich;
•**2014.** S-shaped planar meander slow wave system on dielectric substrate . Luqi Zhang, Yanyu Wei, Chong Ding, Yuanyuan Wang, Minhao Zhang, Lingna Yue, Yubin Gong, Wenxiang Wang. Proceedings of the 15th IEEE International Vacuum Electronic Conference (IVEC-2014), Monterey, CA, USA. DOI: 10.1109/IVEC.2014.6857616];
•**2016.** 2D ring type meander planar slow wave system on dielectric substrate [Chong Ding, et al. Proceedings of the 17th IEEE International Vacuum Electronic Conference (IVEC-2016), Monterey, CA, USA, DOI: 10.1109/IVEC.2016.7561870];
•**2017**. Meander planar slow wave system on dielectric substrate and dielectric pedestal [Chong Ding et al. Proceedings of the 18th IEEE International Vacuum Electronic Conference (IVEC-2017), London. DOI: 10.1109/IVEC.2017.8289576; Ding Chong et al. Journal of Electromagnetic Waves and Applications, DOI: 10.1080/09205071.2017.1358109];
•**2017**. Planar slow wave systems of O-ring meander type for running wave tube of W band [G. Ulisse, V. Krozer. Proceedings of the 18th IEEE International Vacuum Electronic Conference (IVEC-2017), London. DOI: 10.1109/IVEC.2017.8289587];
•**2017.** Meander planar slow wave system on diamond substrate for W band running wave tube [A. Galdetskiy, E. Rakova. Proceedings of the 18th IEEE International Vacuum Electronic Conference (IVEC-2017), London, ISBN 978-1-5090-5916-4/17]

Planar slow-wave structures description



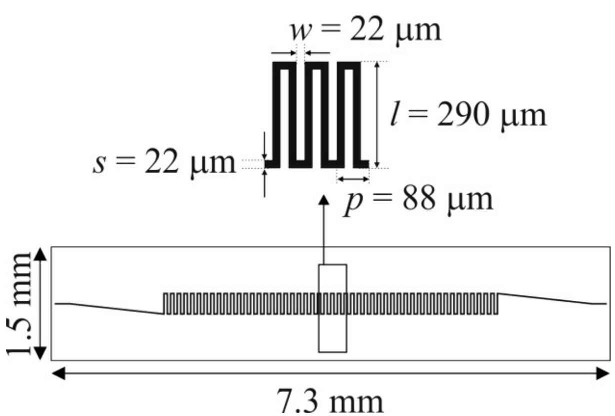
V-band meander-line SWS

Substrate material	**Quartz**
Slow wave structure material	**Copper**
SWS period, *d* (um)	**200**
Metallized strip thickness, *t* (um)	**1÷10**
Substrate thickness, *h* (um)	**500**



W-band meander-line SWS

Substrate material	**Quartz**
Slow wave structure material	**Copper**
SWS period, *d* (um)	**130**
Metallized strip thickness, *t* (um)	**1÷10**
Substrate thickness, *h* (um)	**500**

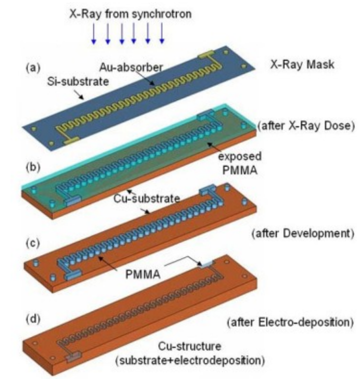


D-band meander-line SWS

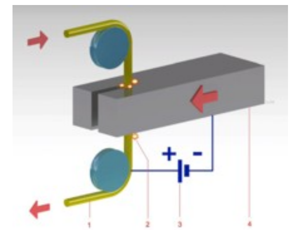
Substrate material	**Quartz**
Slow wave structure material	**Copper**
SWS period, *d* (um)	**88**
Metallized strip thickness, *t* (um)	**1÷10**
Substrate thickness, *h* (um)	**200**

Existing microfabrication technologies for components of vacuum electron devices

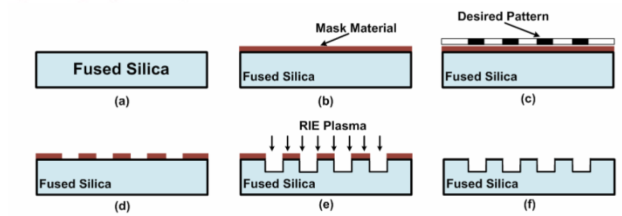
- lithography-based technologies (LIGA, UV-LIGA or SU-8 process)



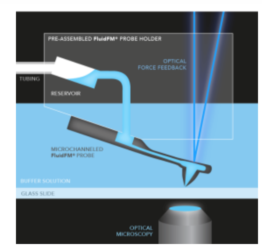
- electric discharge micromachining (EDM)



- deep reactive ion etching (DRIE)



- 3D printing (FluidFM techology, etc.)



- computer numerical control (CNC) micro- and nano-milling

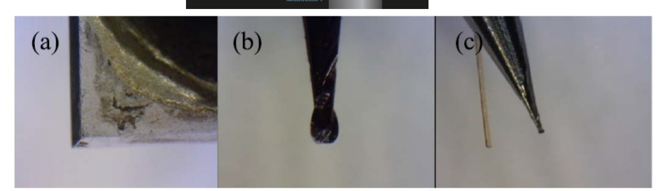


Fig. 1. Tooling used on NN1000. (a) Brazed diamond facing mill. (b) 0.3046-mm diameter bull nose end mill. (c) 0.076-mm diameter end mill shown next to a human hair.

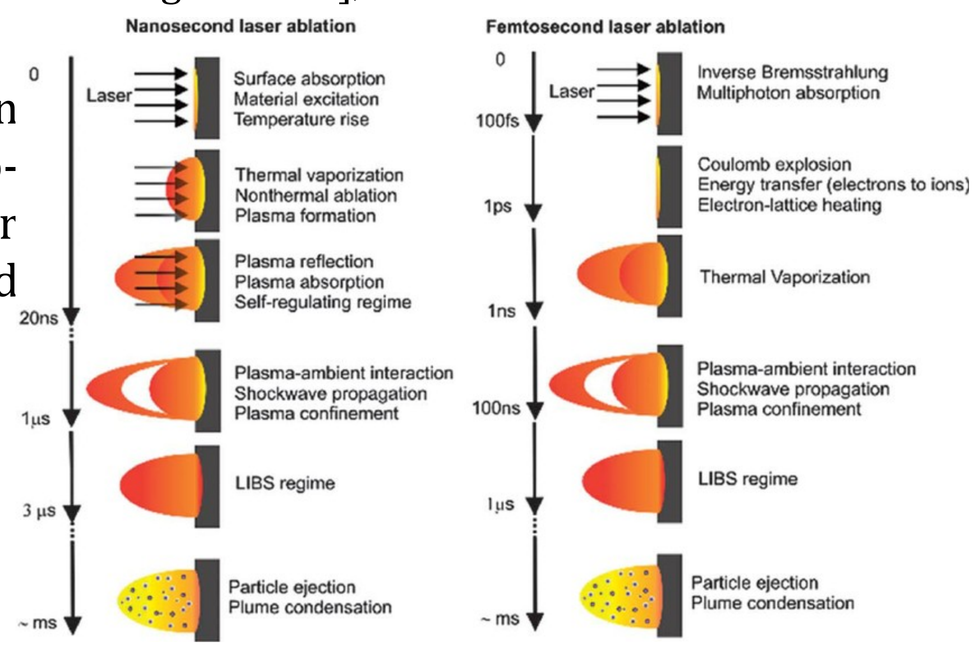
Laser ablation

- Root, RG. Laser-induced plasma and applications, Marcel Dekker, New York, 1989;
- Bauerle, D. Laser processing and chemistry (3rd ed.), Springer-Verlag, Berlin, 2000;
- C. Phipps (ed.), Laser Ablations and its Applications. Springer, Berlin, 2007
- …

- **MEMS components** [S.A. Soper et al. Anal. Chim. Acta 470 (2002) 87–99; J.P. Desbiens, P. Masson, Sens. Actuat., A Phys. 136 (2007) 554–563], microfluidic devices [Waddell E.A. (2006) Laser Ablation as a Fabrication Technique for Microfluidic Devices. In: Minteer S.D. (eds) Microfluidic Techniques. Methods In Molecular Biology™, vol 321. Humana Press],
- **optical waveguides and optical devices components** [S. Li, Y. Ye, M. Wang. Opt. Laser Technol. 58 (2014) 89–93; A. Li, Z. Wang, J. Liu, X. Zeng. Opt. Lasers Eng. 49 (2011) 351–355; W. Kam, Y.S. Ong, W.H. Lim, R. Zakaria. Opt. Lasers Eng. 55 (2014) 1–4],
- **biomedical devices** [C.-H. Hung, F.-Y. Chang. Opt. Laser Technol. 90 (2017) 1–6],
- **nanoparticles synthesis** [Haider, A.F.M.Y., Sengupta, S., Abedin, K.M. et al. Appl. Phys. A (2011) 105: 487; D. Kane, A. Micolich, & J. Rabeau (Eds.), Nanotechnology in Australia: Showcase of early career research. 2011. Singapore: Pan Stanford Publishing Pte. Ltd.],
- etc.

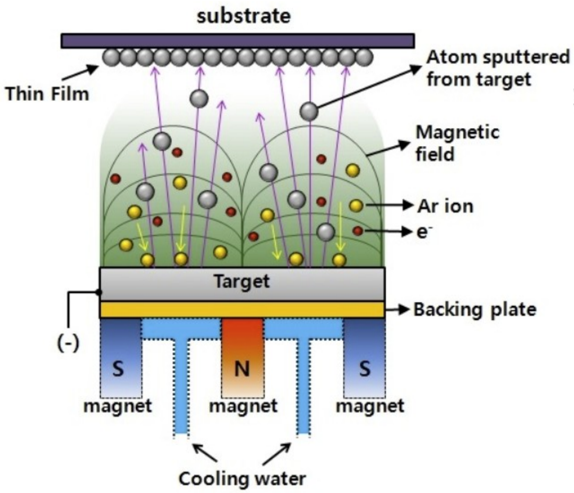
One of the major directions in laser ablation technique development is utilizing of pico- and femto-second lasers which allows for improvement of quality (roughness) and precision of structures manufactured.

Application for microfabrication of vacuum electronic devices components

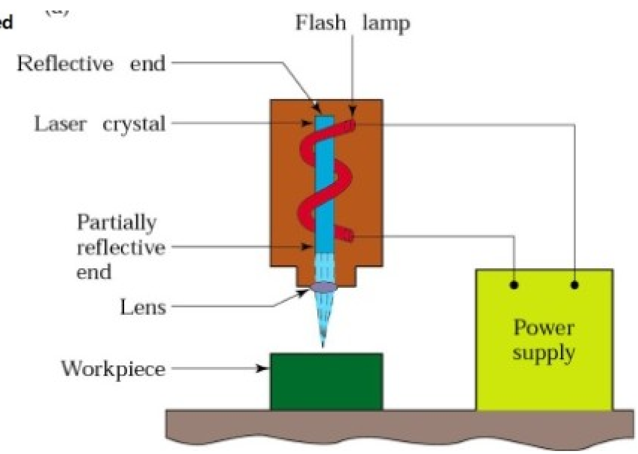


An approach to microfabrication of planar slow-wave structures

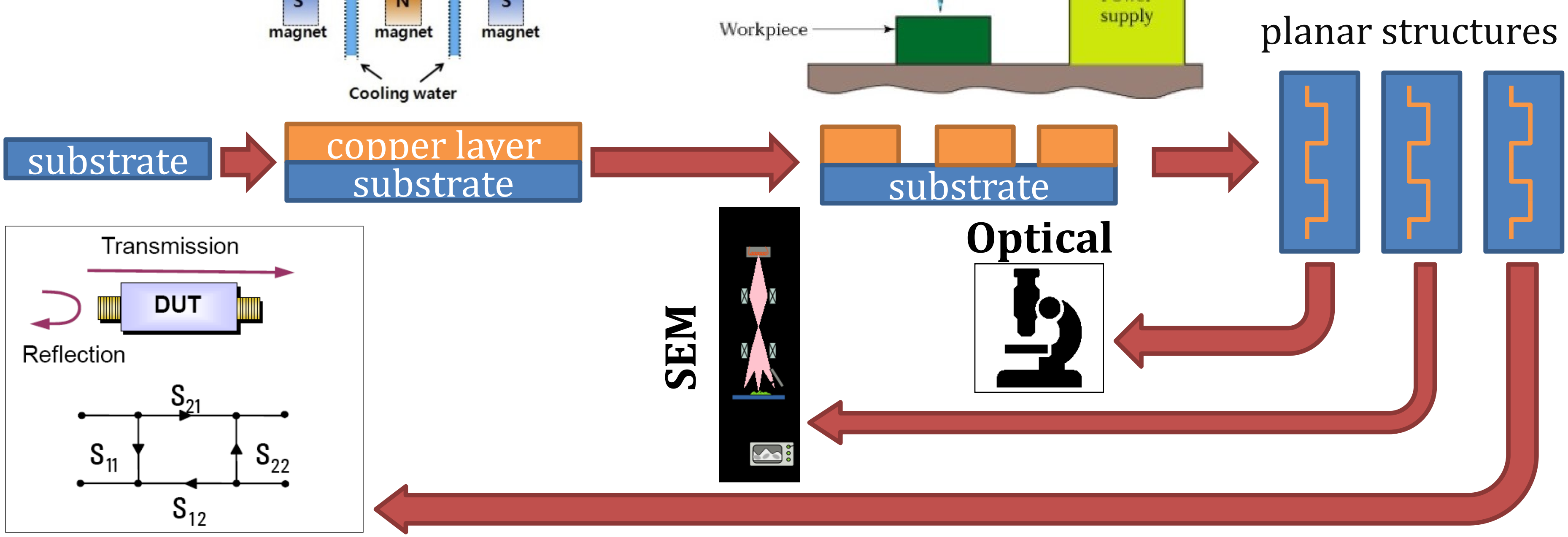
Thin-film deposition by Magnetron sputtering



Laser ablation



Micro Diamond Scriber



Radiophysics

M.C. Gower. Optics Express, Vol. 7, No. 2, 2000, p. 56-57

H.J. Booth. Thin Solid Films, Vol. 453-454 , 2004, p. 450-457

Equipment for microfabrication

Thin-film deposition by magnetron sputtering systems

Robvac VSM300 (Robvac Company, Russia)
Base pressure $5 \cdot 10^{-3}$ Pa,
Working pressure $1{,}9 \cdot 10^{-1}$ Pa.
Working gas – argon
Number of magnetrons: 2 (up to 4)

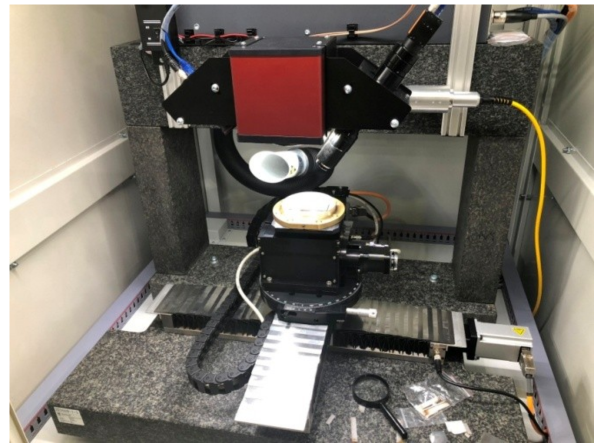
NexDep (Angstrom, Canada)
Base pressure $5 \cdot 10^{-3}$ Pa,
Working pressure $1{,}9 \cdot 10^{-1}$ Pa.
Working gas – argon
Number of magnetrons: 2 (up to 3)

Equipment for microfabrication

CNC picosecond laser ablation system

Picoseconds laser ablation system was based on the laser Rapid 6 (wavelength 1064 nm, Coherent, USA) and scan head (RayLase, Germany). Pulse duration: 10 ps, pulse repetition rate 80 kHz - 1 MHz, laser beam scanning movement speed 200–1000 mm/s.

CNC nanosecond laser ablation system



Ytterbium pulse fiber laser (IPG Photonics, wavelength 1064 nm), scan head (Cambridge Technology), Software and hardware resolution ±2 um, laser spot dimension in focus region ~ 20 um, energy in the laser pulse (max): 1 mJ, pulse duration ~ 4-200ns, pulse repetition rate 20 kHz – 100 kHz, laser beam scanning movement speed ~ 0.1-4000 mm/s

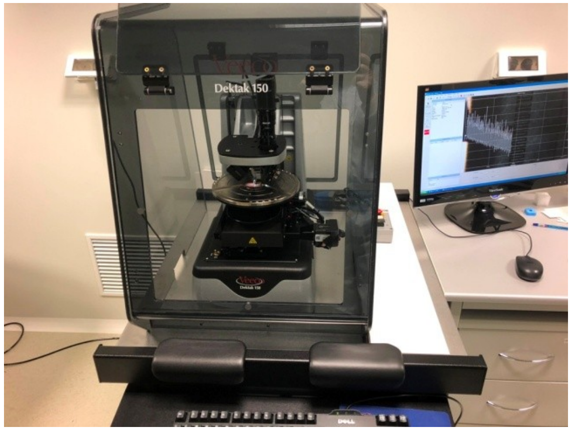
Micro Diamond Scriber

RV-129 (ATV Technologie GmbH, Germany). Precision diamond scriber for manual scribing. Resolution 10 μm.

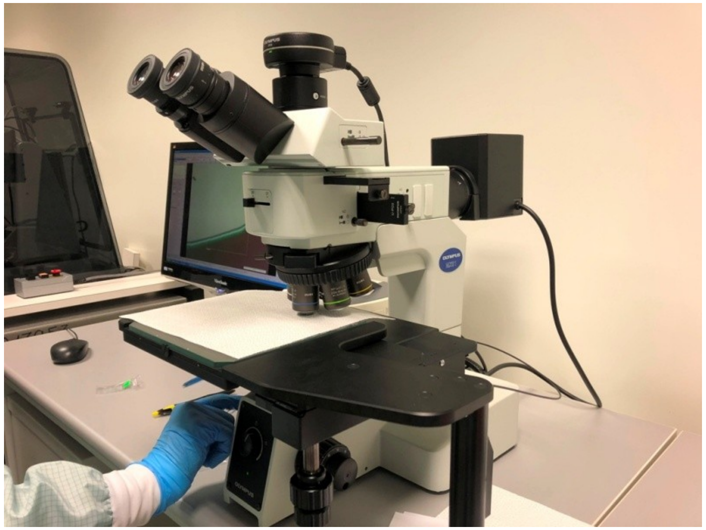
Equipment for study and verification

SEM Tescan Mira II LMU

Inverted optical system
Olympus IX71

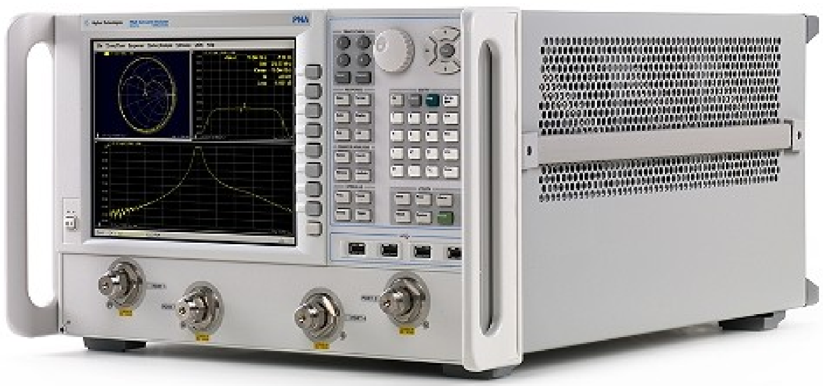


The Dektak® 150
Surface Profiler (Veeco)

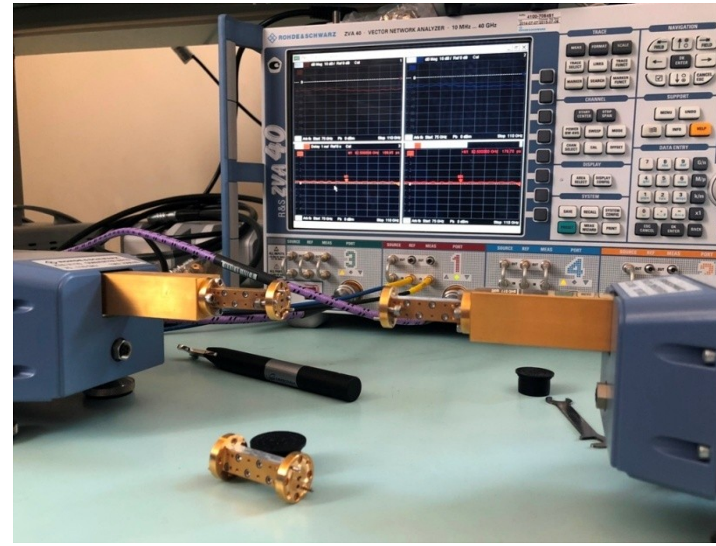


Optical system
Olympus MX51

Equipment for study and verification



Vector network analyzer PNA N5227A, USA
(10MHz-70 GHz)



Vector network analyzer ZVA Z40 with Rx/Tx frequency converters ZVA-Z110 (75-110 GHz), R&S, Germany

Rx/Tx frequency converters ZVA-Z170 (110-170 GHz), R&S, Germany

Rx/Tx frequency converters ZVA-Z260 (170-260 GHz), R&S, Germany

Microfabrication by nanosecond laser ablation

Laser ablation of materials begins with the absorption of photons, followed by heating and photoionization of the target region by a laser beam. Subsequently, ablated materials are released from the target surface in the form of solid fragments, vapors, liquid droplets, or as an expanding plasma torch. The amount of depleted material and phase depends on the energy absorbed by the target material. In general, three different laser pulse duration regimes are distinguished: regime with long pulse duration, such as nanosecond pulse duration, with short pulse duration (picosecond laser) and with ultra-short pulse duration (femtosecond laser).

Main disadvantages:

the surface of the target material are heated to melting point and then to vaporisation temperature

enough time for thermal waves to propagate into the target material

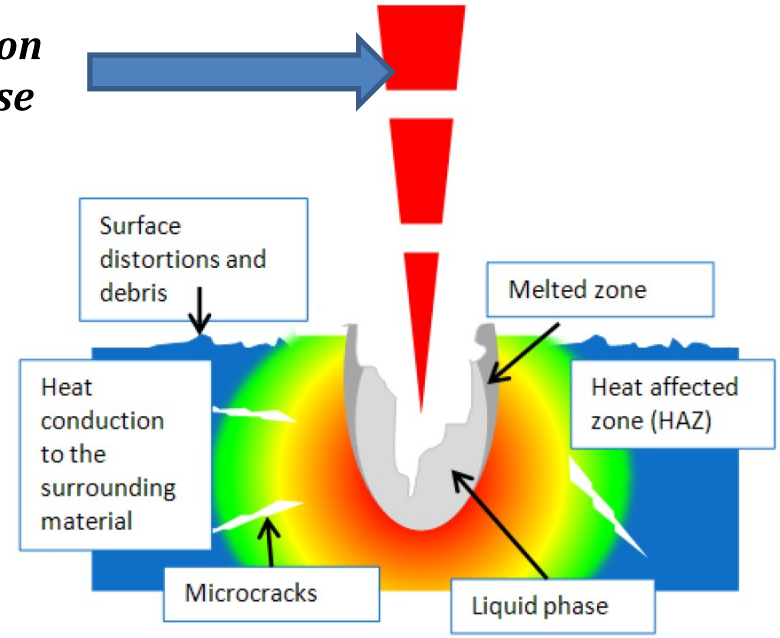
Melted zone

Microcracks

Surface distortions and debris

This poses a real challenge for precision laser processing with nanosecond laser pulses

long pulse duration (nanosecond pulse duration)

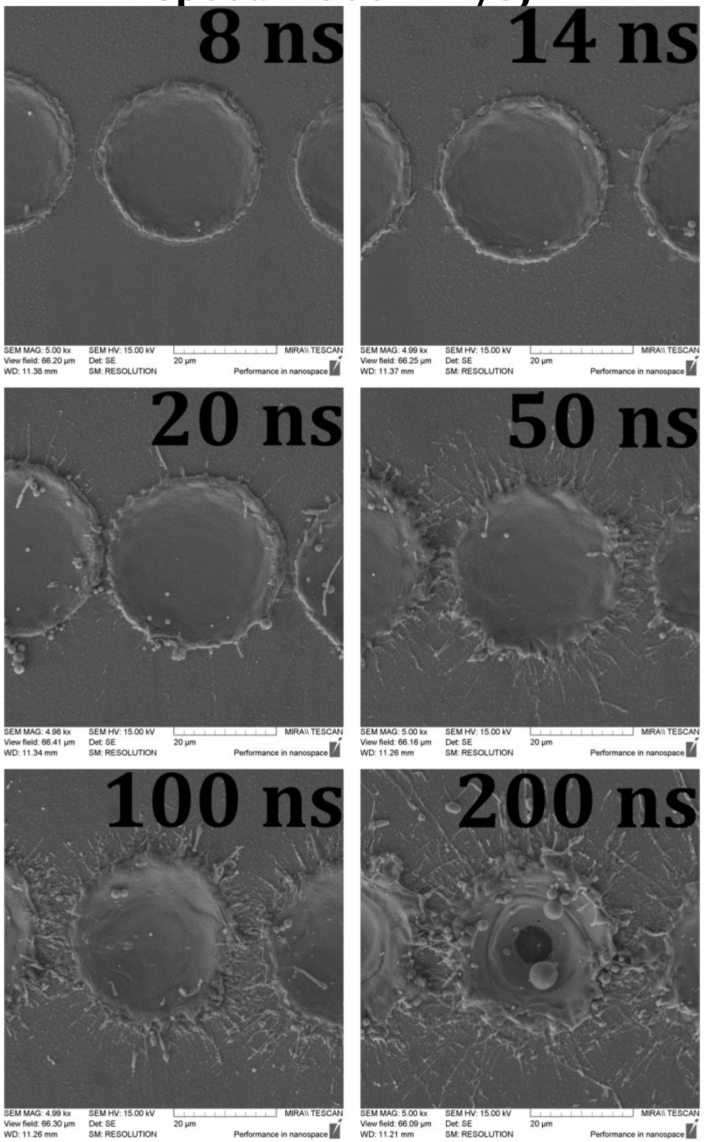


Main advantages: speed and equipment cost

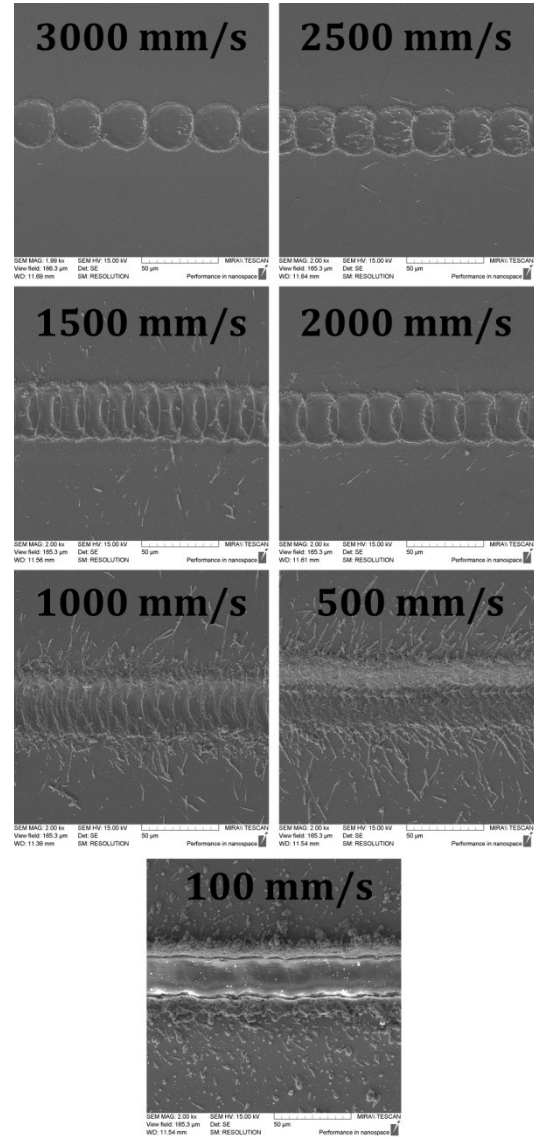
1. Jaeggi, B., B. Neuenschwander, M. Schmid, M. Muralt, J. Zuercher and U. Hunziker, Influence of the pulse duration in the ps-regime on the ablation efficiency of metals. Physics Procedia, 2011. 12: pp. 164–171. doi:10.1016/j.phpro.2011.03.118
2. Momma, C., B.N. Chichkov, S. Nolte, F. von Alvensleben, A. Tünnermann, H. Welling and B. Wellegehausen, Short-pulse laser ablation of solid targets. Optics Communications, 1996. 129(1): pp. 134–142. doi:10.1016/0030-4018(96)00250-7
3. Lucas, L. and J. Zhang, Femtosecond laser micromachining: a back-to-basics primer. 2012, http://www.industrial-lasers.com/

Nanosecond laser ablation

Demonstration of the melted zone, surface distortions, and debris while pulse duration increasing (laser beam speed 4000 mm/s)

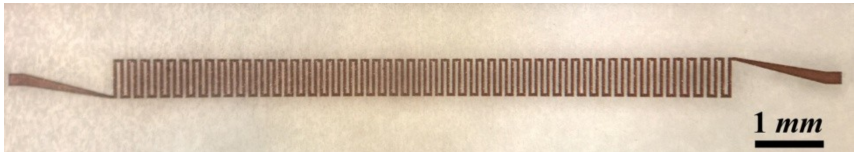


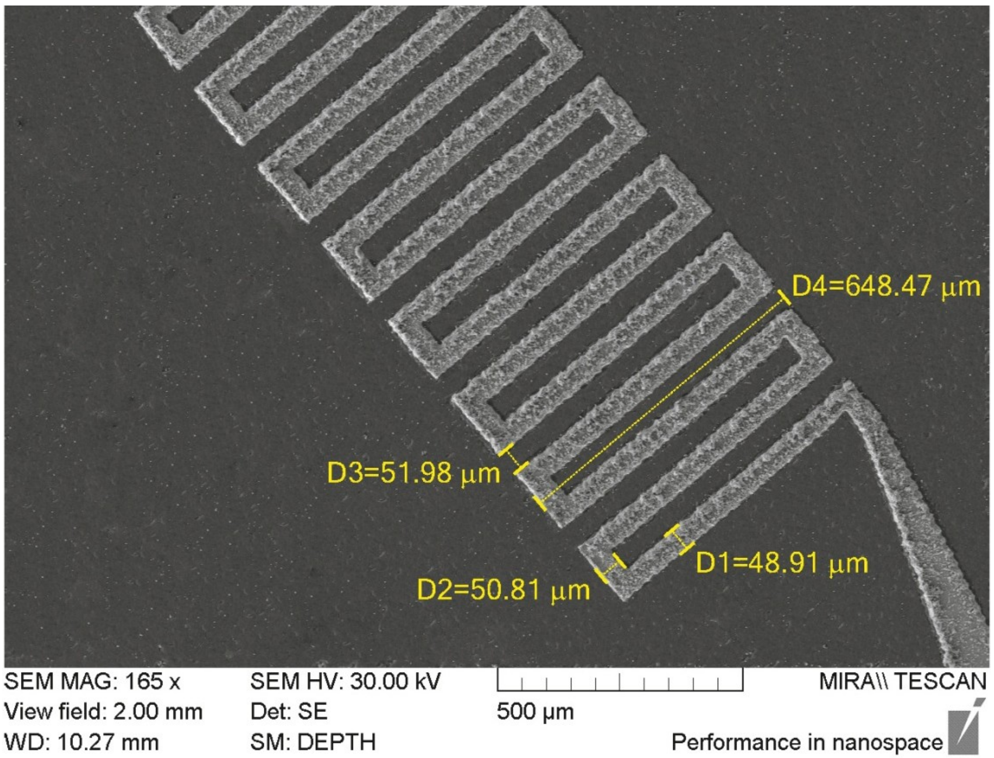
Demonstration of melted zone, surface distortions and debris while laser beam speed decreasing



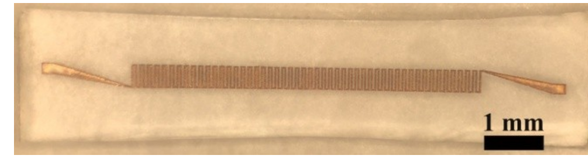
Nanosecond laser ablation

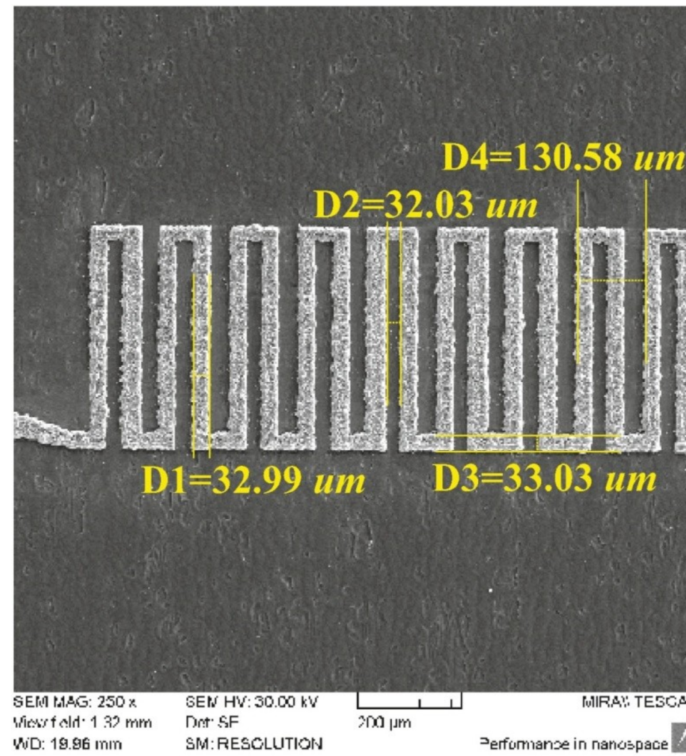
Meander-line V-band SWS





Meander-line W-band SWS

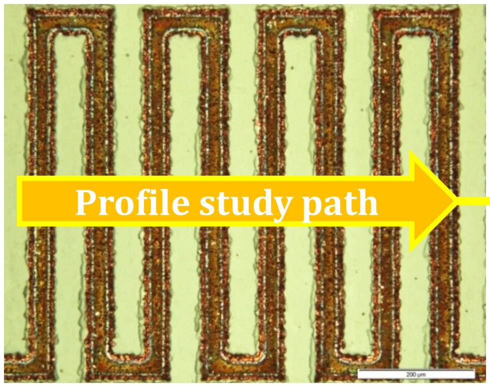




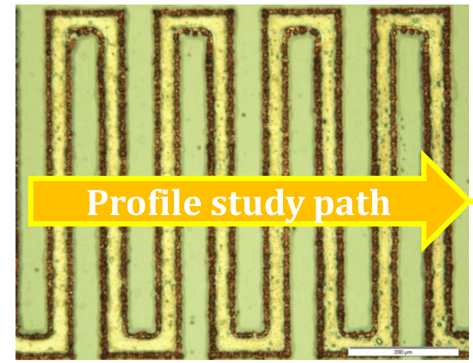
1. Ryskin, N.M., *et al.* "Planar Microstrip Slow-Wave Structure for Low-Voltage V-band Traveling-Wave Tube with a Sheet Electron Beam," IEEE Electron Device Letters, vol. 39, no. 5, pp. 757-760, 2018
2. Torgashov, R.A., *et al.* "Theoretical and Experimental Study of a Compact Planar Slow-Wave Structure on a Dielectric Substrate for the *W*-Band Traveling-Wave Tube". *Tech. Phys.* **65,** 660–665 (2020). https://doi.org/10.1134/S1063784220040222

Nanosecond laser ablation

Meander-line V-band SWS

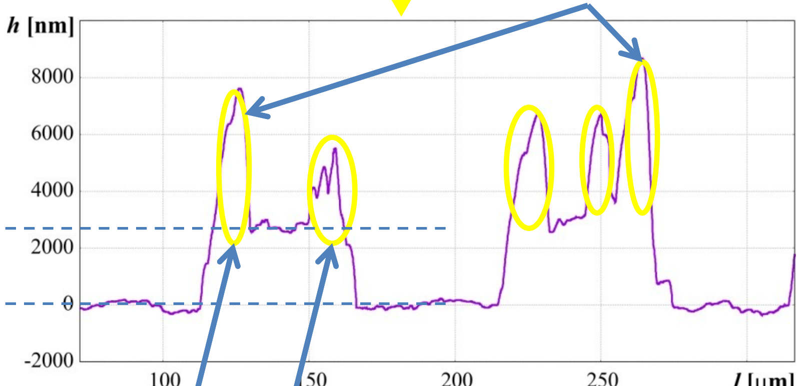


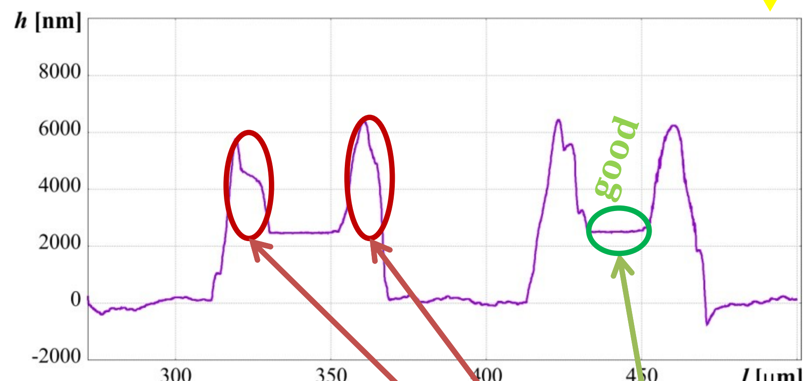
Mechanical post processing
(sonication)

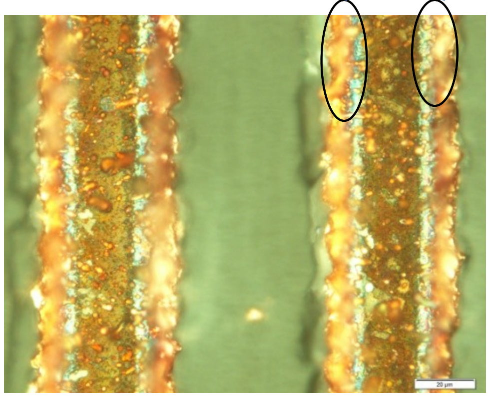


Surface distortions and debris

Thin-film thickness

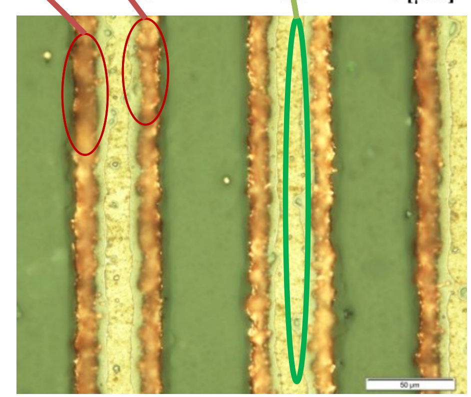






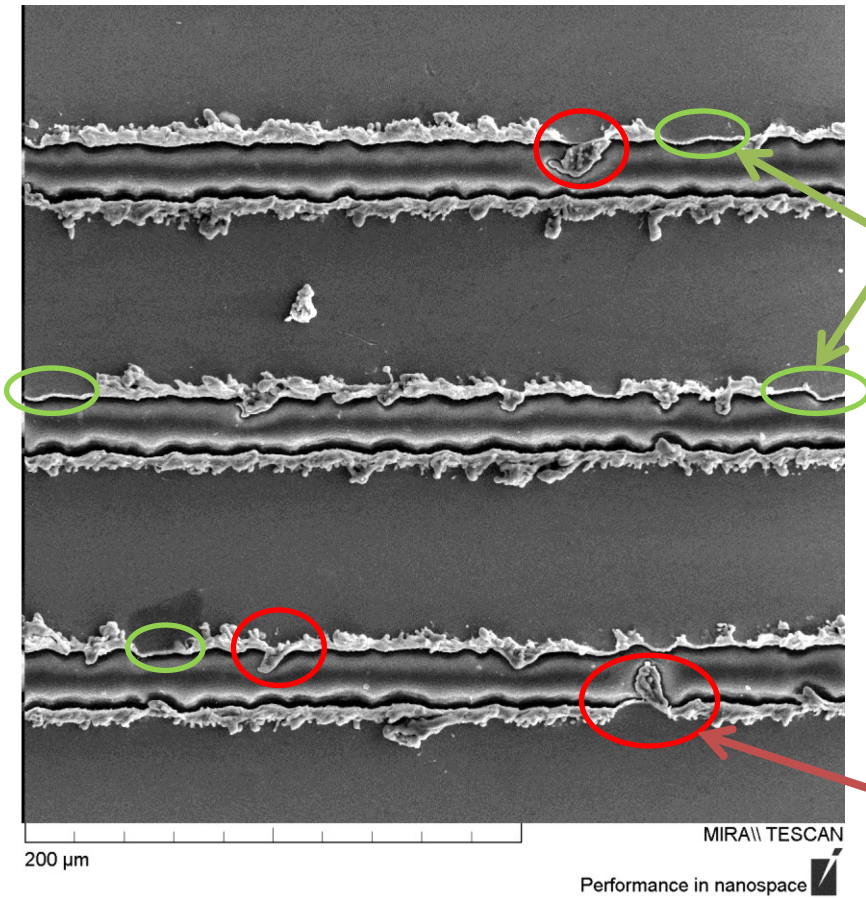
the peripheral zone has changed slightly, although the surface distortions have become thinner and lower

the central zone has become much better



Nanosecond laser ablation

Acid Post processing

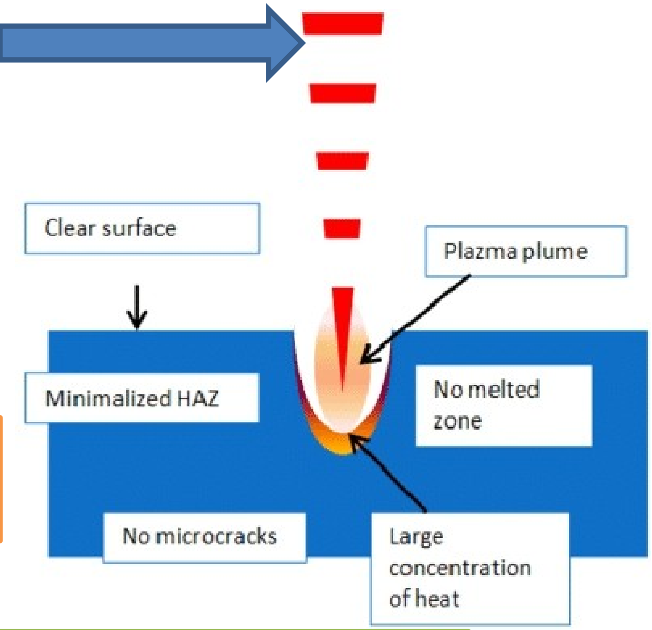


The cleared surface of thin-film after laser ablation with nanosecond pulses

moment of separation of debris from a thin-film surface

Picosecond laser ablation

Short/ultra-short pulse duration (pico/femto -second pulse duration)



In the case of short (picosecond) and ultra-short laser pulses (femtosecond), the timescale required for energy transfer between the lattice and the free electrons of the material target is considerably longer than pulse duration

the material quickly heats up and directly reaches the vapor phase without passing through the melting point

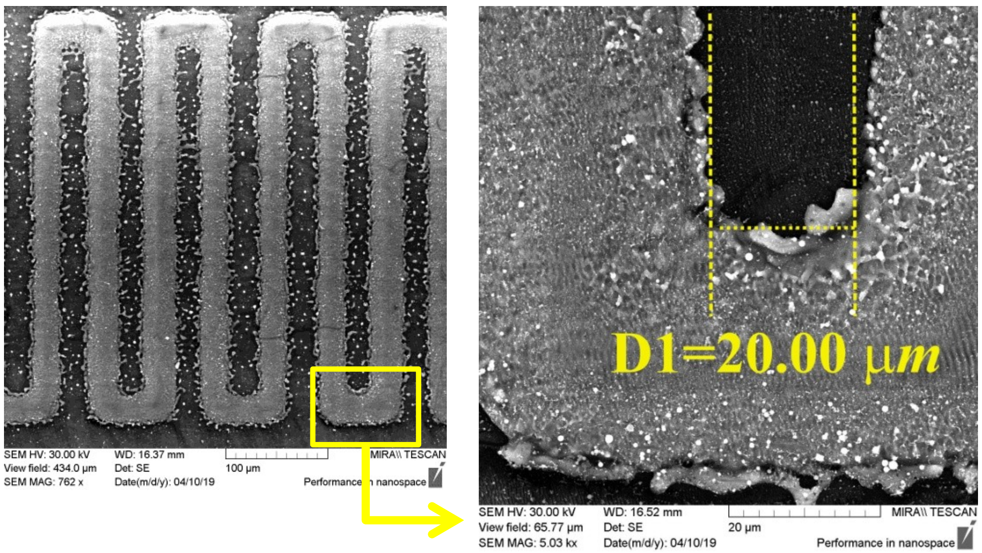
No melted zone (almost) ***No microcracks*** ***Surface distortions and debris are almost absent***

The ablated area is very precise and smooth without forming any observable heat-affected zone

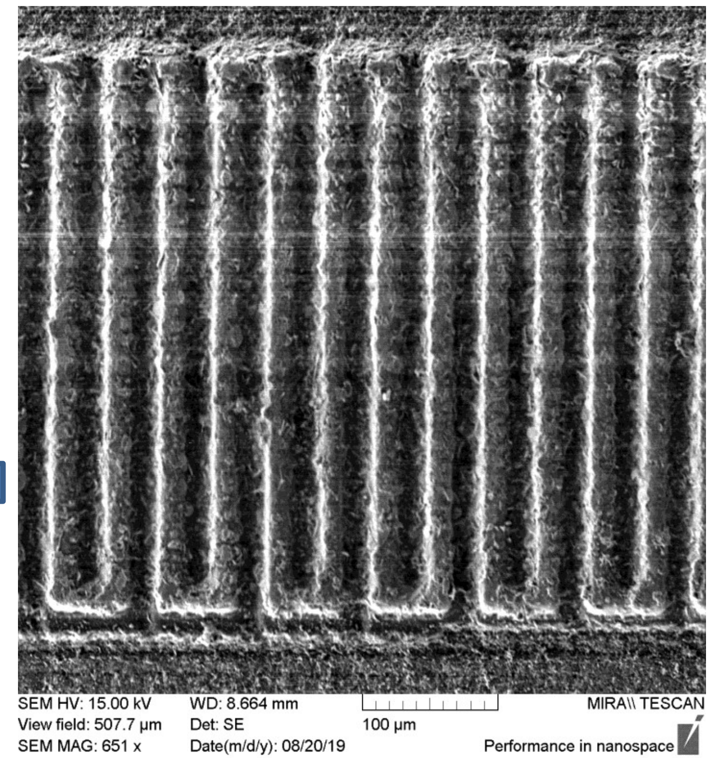
Main disadvantages: speed and equipment cost

1. Abubaker Hassan Hamad (September 7th 2016). Effects of Different Laser Pulse Regimes (Nanosecond, Picosecond and Femtosecond) on the Ablation of Materials for Production of Nanoparticles in Liquid Solution, High Energy and Short Pulse Lasers, Richard Viskup, IntechOpen, DOI: 10.5772/63892
2. K. Sugioka and Y. Cheng, "Femtosecond laser three-dimensional micro-and nanofabrication," *Appl. Phys. Rev.*, vol. 1, no. 4, 2014, doi: 10.1063/1.4904320.
3. M. M. Mielke *et al.*, "Applications of ultrafast lasers in microfabrication," *J. Laser Micro Nanoeng.*, vol. 8, no. 2, pp. 115–123, 2013, doi: 10.2961/jlmn.2013.02.0001.
4. W. J. Keller *et al.*, "Physics of picosecond pulse laser ablation," *J. Appl. Phys.*, vol. 125, no. 8, 2019, doi: 10.1063/1.5080628.

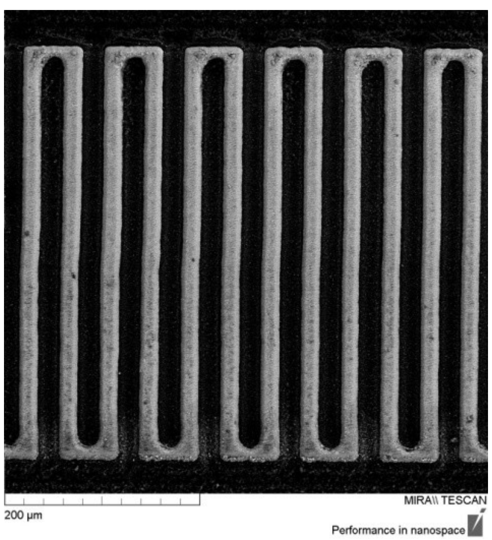
D-band meander-line SWS microfabrication by picosecond laser ablation



just after microfabrication by picosecond laser ablation



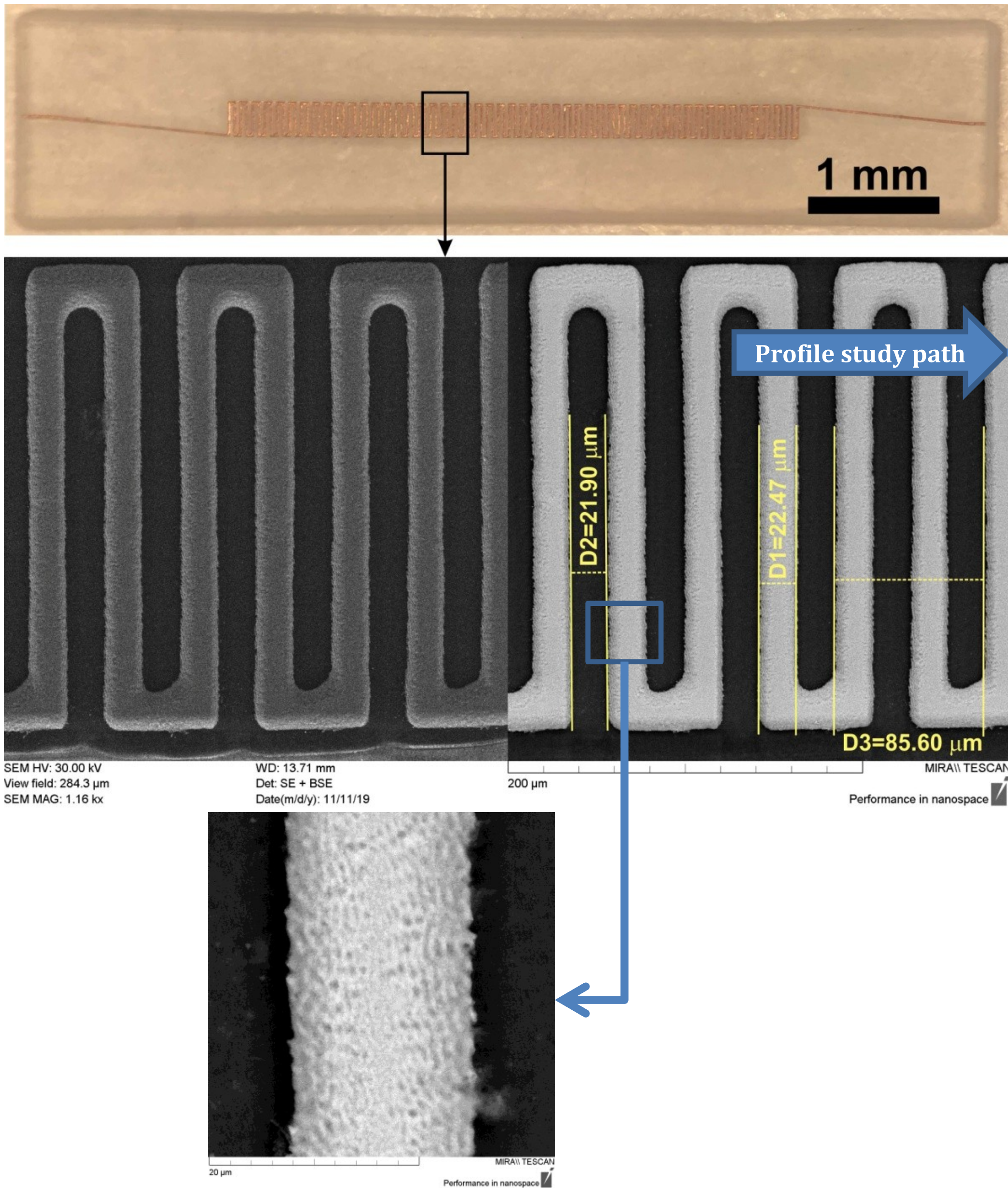
after post processing

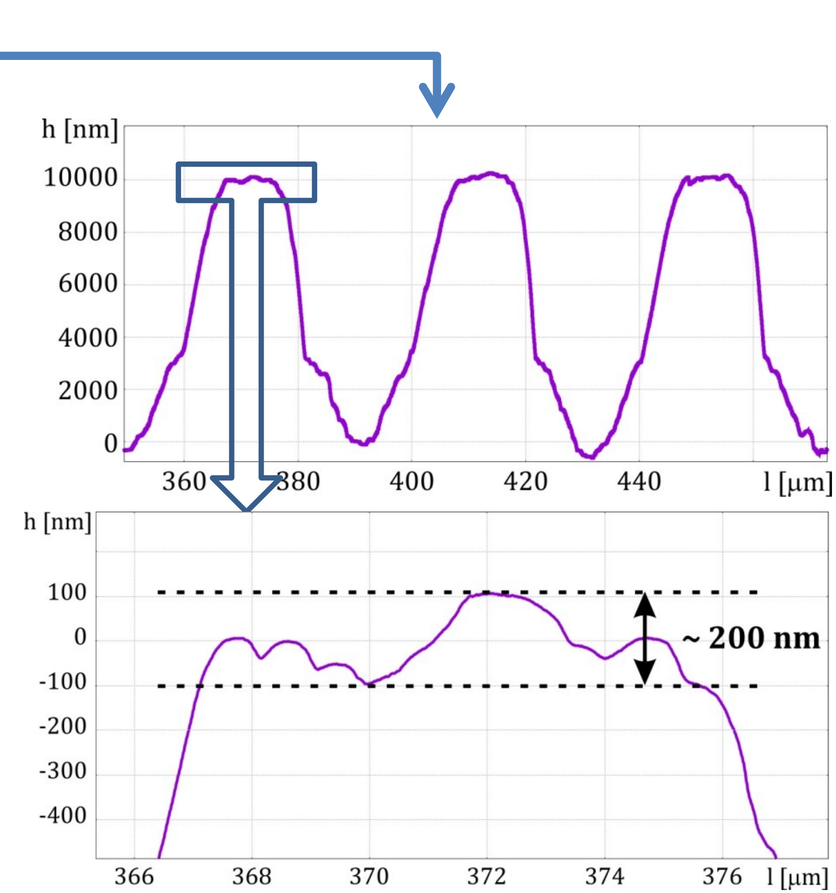


Andrey V. Starodubov, *et. al.* Proc. SPIE 11458, Saratov Fall Meeting 2019: Laser Physics, Photonic Technologies, and Molecular Modeling, 1145803 (9 April 2020); doi: 10.1117/12.2564423

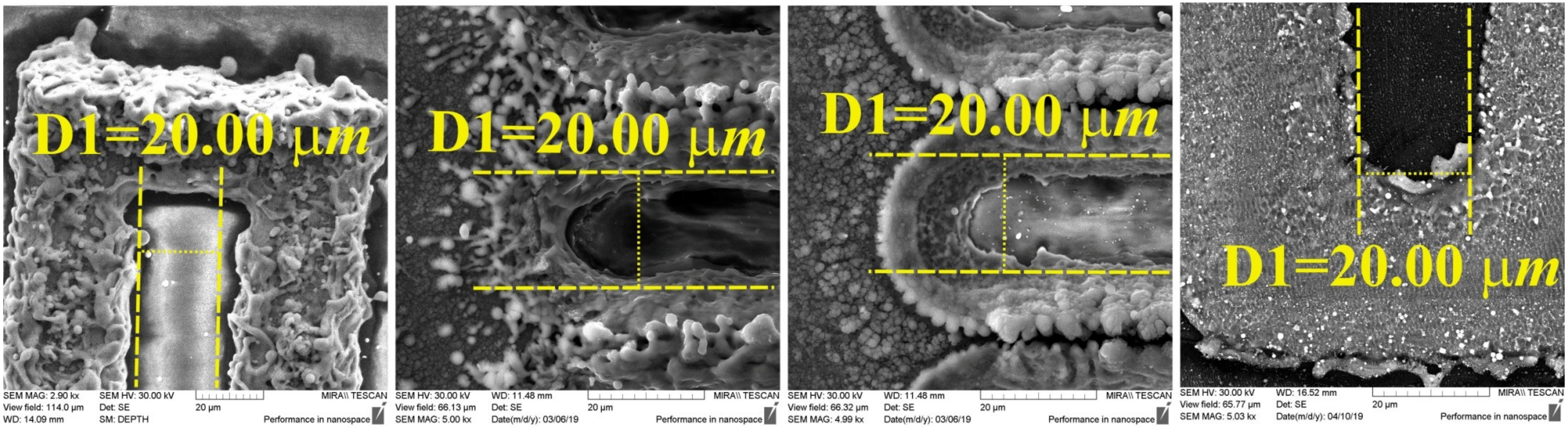
D-band meander-line SWS microfabrication by picosecond laser ablation

Optical and SEM images of the D-band meander-line SWS





Conclusions



Pulse duration 100 ns | **Pulse duration 14 ns** | **Pulse duration 4 ns** | **Pulse duration 10 ps**

Long (nanosecond) pulse laser ablation:

- High speed of manufacturing and low cost of equipment;
- Post-processing is strongly required – it is a real challenge.

Short (picosecond) pulse laser ablation:

- Relatively low speed of manufacturing and high cost of equipment (up to 10 and more times);
- post-processing is easy and gives excellent results

Future work:

1. An attempt of using the ultra-short (femtosecond) laser ablation for expansion of the proposed technology for the manufacturing of higher-frequency G-band (170-260 GHz) planar SWSs

Thank you for your attention!

- To Program and Organizing Committee!
- To Chairmen of the Section!
- To All Listeners!
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