Supplementary Information

Air-hole geometry design of ram-extruded polytetrafluoroethylene coaxial cables for low-loss and reproducible operation

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Supplementary Note 1: Process routes for air regions in PTFE coaxial dielectrics

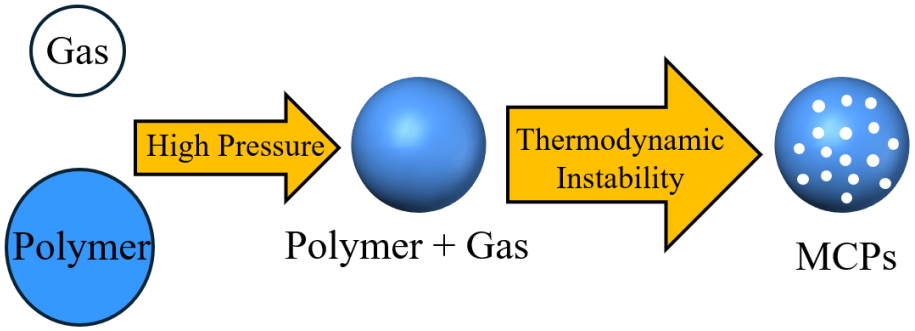
This note compares three process-based methods for forming air regions in coaxial cable dielectrics: foam extrusion, dual extrusion and ram extrusion. Process-based methods can be integrated into extrusion without filler materials or post-processing. Each method is described by its working principle, manufacturability, structural uniformity and mechanical stability, and the comparison motivates the use of ram extrusion in the main text.

Foam extrusion. Foam extrusion lowers the dielectric constant by generating micro-cells within the polymer matrix. A supercritical gas is dissolved into the molten polymer under high pressure and low temperature. A subsequent change in pressure or temperature induces thermodynamic instability, causing phase separation and micro-cell formation (Supplementary Fig. 1a). The resulting micro-cellular polymer contains closed cells that reduce both density and effective permittivity, and the technique has been widely applied to polyethylene-based dielectrics for coaxial cables. During extrusion, the gas-polymer mixture is fed continuously into the extruder (Supplementary Fig. 1b); gas is injected through a high-pressure inlet and dispersed within the polymer melt by screw rotation. Stable cell formation requires precise control of pressure, gas concentration and temperature gradient. Uniform bubble nucleation under high temperature and pressure is difficult to achieve, and maintaining consistent cell morphology over long cable lengths requires complex equipment and strict process control.

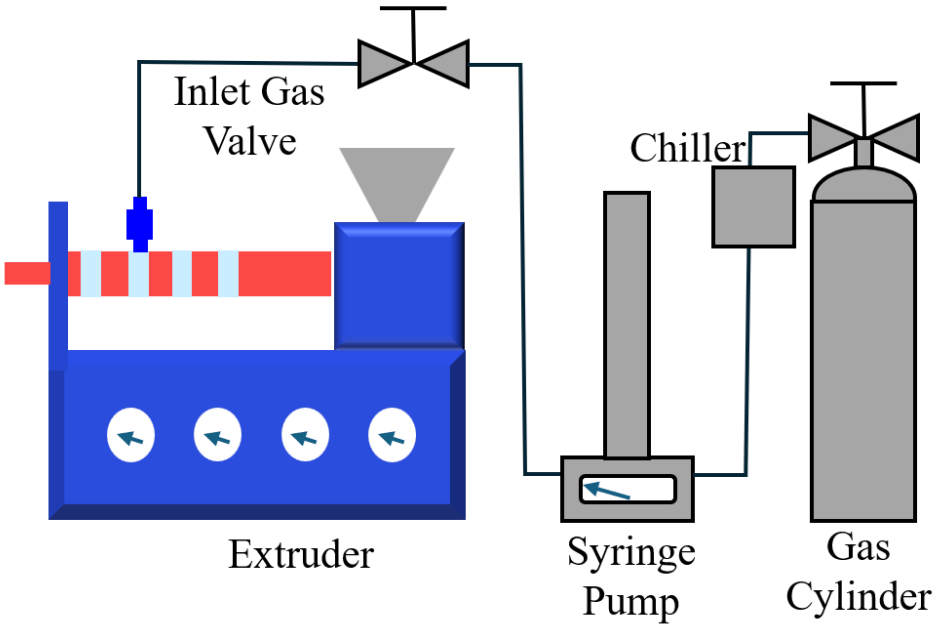
Dual extrusion. Dual extrusion involves two successive extrusion steps (Supplementary Fig. 2). A primary extrusion produces a straight dielectric rod (Supplementary Fig. 2a), which is then covered or reshaped by a secondary extrusion to form the final circular geometry (Supplementary Fig. 2b). Because PTFE cannot be melt-processed, dual extrusion is one of the representative methods for PTFE-based coaxial cables. It allows precise control of the dielectric shape and dimensional uniformity, but repeating the extrusion increases total manufacturing time, and the secondary process requires extra dies and tooling, which raises mechanical complexity and cost. Its limited efficiency makes it less suitable for continuous production.

Ram extrusion. Ram extrusion is the other primary method for PTFE-based cables. It consists of four stages (Supplementary Fig. 3). PTFE powders are first blended for homogeneity. In the preforming stage the powder is compressed in a mould under controlled temperature and pressure to produce a rod, removing trapped air and impurities and increasing density. The preform is then placed in a ram extruder and forced through a die under high pressure to obtain the desired geometry. Finally, sintering at approximately 330 °C completes the structure and gives the dielectric the mechanical strength and electrical stability required for coaxial cables. Compared with dual extrusion, ram extrusion forms continuous and longitudinally uniform structures with precise dimensional control and reproducibility. Because the extrusion proceeds by solid-state compaction rather than melt flow, the dielectric has good mechanical

integrity and surface quality with minimal unintended porosity. Supplementary Table 1 summarizes the comparison.



(a)

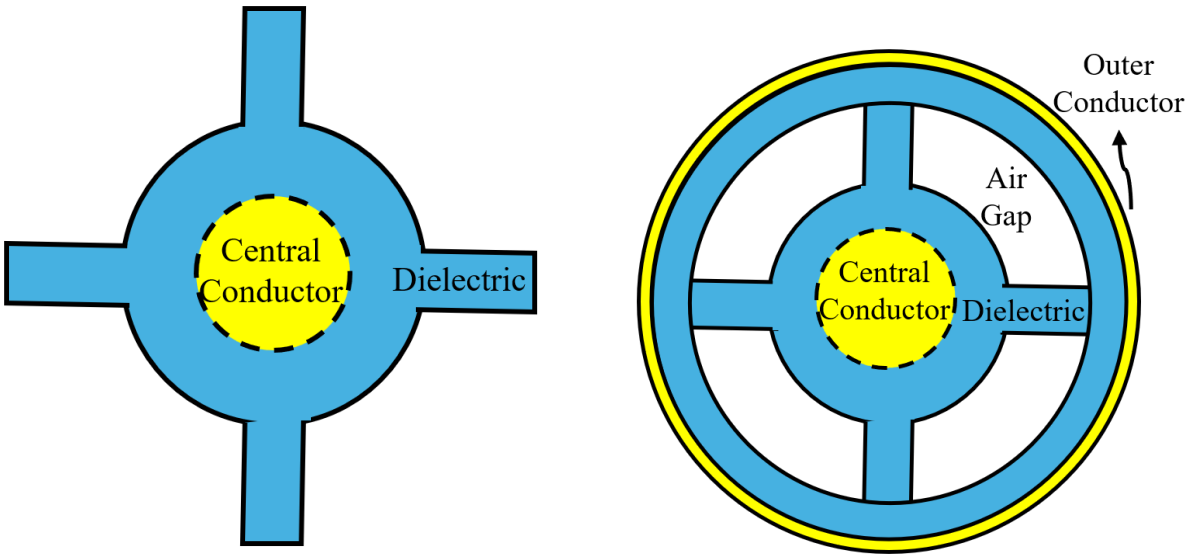


(b)

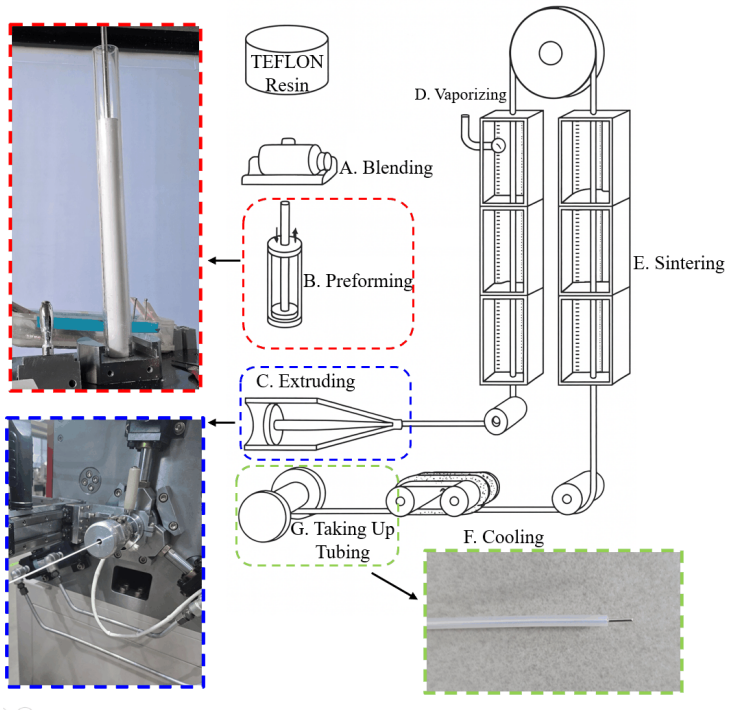
Supplementary Fig. 1: Foam extrusion process for dielectric fabrication. **a**, Mechanism of micro-cell generation under thermodynamic instability. **b**, Extrusion system with gas injection into the polymer melt (adapted from ref. [1]).

Supplementary Table 1: Comparison of process-based dielectric fabrication methods for coaxial cables.

Method	Air structure	Process complexity	Geometry control	PTFE suitability
Foam extrusion	Random pores	High	Moderate	Limited
Dual extrusion	Controlled shape	High	High	Moderate
Ram extrusion	Longitudinal holes	Moderate	High	High



Supplementary Fig. 2: Dual extrusion process for dielectric fabrication. **a**, Primary extrusion of the dielectric rod. **b**, Secondary extrusion forming the final circular geometry (adapted from ref. [2]).



Supplementary Fig. 3: Ram extrusion process for the PTFE dielectric: blending, preforming, extruding and sintering.

Supplementary Table 2: Electromagnetic simulation settings.

Item	Description
Solver	3-D EM field simulator
Solver type	Time domain (finite integration)
Boundary condition	Open (add space), all directions
Frequency range	0–18 GHz
Mesh type	Hexahedral mesh
Mesh density	$\geq$ 15 cells per wavelength
Accuracy (energy decay)	-40 dB
Inner conductor radius	$a = 0.4$ mm (fixed)
Outer PTFE radius	b, set for 50 Ω
Conductor material	Copper
Electrical conductivity	5.8×10^7 S/m
Dielectric material	PTFE
Relative permittivity	$\varepsilon_r = 2.1$
Loss tangent	$\tan\delta = 0.0002$ at 10 GHz
Dielectric loss model	Causal dispersion fit ($N = 3$)

Supplementary Table 3: Geometric parameters of the simulated cable cross sections (mm for lengths, degrees for angles).

Common parameters					
a_1	0.40	b_1	1.23	b_2	1.20
b_3	1.17	b_4	1.13	b_5	1.11
b_6	1.13	b_7	1.01	b_8	1.13
b_9	1.06	r_1	0.65	r_2	0.70
r_3	0.75	r_4	0.80	s_1	1.15
s_2	0.49	s_3	0.23	s_4	0.046
θ_1	120	θ_2	60	θ_3	40
θ_4	30				
Air-hole diameters[a]					
d_1	0.30	d_2	0.33	d_3	0.42
d_4	0.27	d_5	0.24	d_6	0.60
d_7	0.67	d_8	0.83	d_9	0.54
d_{10}	0.48	d_{11}	0.50	d_{12}	0.56
d_{13}	0.69	d_{14}	0.45	d_{15}	0.40
d_{16}	0.40	d_{17}	0.44	d_{18}	0.56
d_{19}	0.36	d_{20}	0.32		

[a]For a deformed hole, $d_{\mathrm{major}} = d/k$ and $d_{\mathrm{minor}} = d \cdot k$, with $k_1 = 0.9$ and $k_2 = 0.8$.

Supplementary References

[1] Jeon, B. J., Cha, S. W. & Lee, K. S. *A study on the foaming characteristics of the insulator for the coaxial cable*. in Proc. Korean Soc. Mech. Eng. (KSME) Conf. (Seoul, Republic of Korea, 2010).

[2] Ishii, T., Matsuno, S., Watanabe, K. & Tanaka, S. Thin-diameter coaxial cable and method of producing the same (2005). U.S. Patent Appl. 2005/0230145 A1.