

## List of Symbols

<b>Symbol</b>		<b>page</b>
$L^2$	Hilbert space	1
$L^\infty$	Essential Lebesgue space	2
$\ell^1$	Lebesgue space	2
$\ell^p$	Lebesgue space	2
$a.e$	Almost every where	3
$ess\ inf$	essential infimum	4
$ess\ sup$	essential supremum	4
$mod$	Modular	18
$supp$	Support	22
$dim$	Dimension	59
$\otimes$	Tensor product	94
$det$	Determinant	106
$\oplus$	Direct sum	116
$S_p$	Schatten class	161
$STFT$	Short- time fourier transform	163
$OP$	Operator	169
$a.a$	almost all	182
$L^1$	Lebesgue integral on the line	185
$M_m^{p,q}$	Modulation	198
$ker$	Kernel	216

## References

- [1] Peter G. Casazza \* and Ole Christensen . Gabor frames over irregular lattices .November 26 , 2002 .
- [2] Feichtinger, H.G. and Grochenig, K.: Banach spaces related to integrable group representations and their atomic decomposition. J. Funct. Anal. 86 (1989), 307-340.
- [3] Christensen, O.: Atomic decomposition via projective group representations. Rocky Mountain J. Math. 6 No. 1 (1996), 1289-1312.
- [4] Grochenig, K.H.: Describing functions: atomic decompositions versus frames. Monatsh. Math., 112 (No. 1):1-42, 1991.
- [5] Sun, W. and Zhou, X.: Irregular wavelet/Gabor frames. Appl. Comp. Harm. Anal., to appear.
- [6] Bittner, K. and Chui, C.K. Gabor frames with arbitrary windows. Approximation Theorie X, C.K. Chui, L.L. Schumakes and J. Steckler Eds. Vanderbilt University Press, 2002.
- [7] Olsen, P.A. and Seip, K.: A note on irregular discrete wavelet transforms, IEEE Trans. Inform theory, 38 (No.2, Part 2) (1992), p. 861-863.
- [8] Grochenig, K.H.: Irregular sampling of wavelet and short time Fourier transforms. Constr. Approx. 9 (1993) 283-297.
- [9] Feichtinger, H.G.: Private communication.
- [10] Casazza, P.G. and Kalton, N.J.: Roots of complex polynomials and Weyl-Heisenberg frame sets. Proc. Amer. Math. Soc. (to appear).
- [11] Janssen, A.J.E.M.: Zak transforms with few zeroes and the tie. In: Advances in Gabor analysis, Eds. H.G. Feichtinger and T. Strohmer. Birkhäuser, 2002.
- [12] Ramanthan, J. and Steger, T.: Incompleteness of sparse coherent states. Appl. and Comp. Harmonic Analysis, 2 (1995) p.148-153.

- [13] Seip, K. and Wallsten, R.: Sampling and ointerpolation in the Bargmann- Fock space II. *J. Reine Angew. Math.* 429 (1995) 107-113.
- [14] Feichtinger, H.G.: Banach convolution algebras of Wiener's type. In "Proceedings, Conference on functions, series, operators, Budapest 1980, 509-524. *Colloq. Math. Soc. Janos Bolyai*, North-Holland, Amsterdam,1983.
- [15] Daubechies, I.: The wavelet transform, time-frequency localization and signal analysis. *IEEE Trans. Inform. Theory*, 36 (5).
- [16] Walnut, D.: Weyl-Heisenberg wavelet expansions: existence and stability in weighted spaces. Ph.D. thesis, University of Maryland, College Park, M.D., 1989.
- [17] Heil, C. and Walnut, D.: Continuous and discrete wavelet transforms, SIAM Review, 31 (4) (1989) 628-666.
- [18] Janssen, A.J.E.M.: The duality condition for Weyl-Heisenberg frames. In: Gabor analysis: theory and application, Eds. H.G. Feichtinger and T. Strohmer. Birkhäuser, 1998.
- [19] Casazza, P.G. and Lammers, M.C.: Analyzing the Gabor frame identity, Preprint.
- [20] Casazza, P.G., Christensen, O. and Janssen, A.J.E.M.: Weyl-Heisenberg frames, translation invariant systems and the Walnut representation *Journal of Functional Analysis*, 180 (2001) 85-147.
- [21] Feichtinger, H. G. and Janssen, A.J.E.M.: Validity of WH-frame conditions depends on lattice parameters. *Appl. Comp. Harm. Anal.* 8 (2000)104-112.
- [22] Casazza, P.G. and Christensen, O.: Weyl-Heisenberg frames for sub- spaces of  $L^2(\mathbb{R})$ . *Proc. Amer. Math. Soc.* 129 (2001), 145-154.
- [23] Sun, W. and Zhou, X.: On the stability of Gabor frames *Adv. in Appl.Math.* 26 (2001), 181-191.

- [24] Christensen, O., Deng, C. and Heil, C.: Density of Gabor frames. *Applied and Computational Harmonic Analysis* 7 (1999) 292–304.
- [25] Jaffard, S.: A Density criterion for frames of complex exponentials. *Michigan Math. J.* 38 (1991) 339–348.
- [26] Yang Wang . Sparse complete Gabor systems on a lattice  $\star$ . *Appl. Comput. Harmon. Anal.* 16 (2004) 60–67
- [27] D. Gabor, Theory of communication, *J. Inst. Elec. Eng. (London)* 93 (1946) 429–457.
- [28] J. Ramanathan, T. Steger, Incompleteness of sparse coherent states, *Appl. Comput. Harmon. Anal.* 2 (1995) 148–153.
- [29] M.A. Rieffel, Von Neumann algebras associated with pairs of lattices in Lie groups, *Math. Ann.* 257 (1981) 403–413.
- [30] A. Janssen, Signal analytic proofs of two basic results on lattice expansions, *Appl. Comput. Harmon. Anal.* 1 (4) (1994) 350–354.
- [31] J. Benedetto, C. Heil, D. Walnut, Differentiation and the Balian–Low theorem, *J. Fourier Anal. Appl.* 1 (4) (1995) 355–402.
- [32] H. Landau, A sparse regular sequence of exponentials closed on large sets, *Bull. Amer. Math. Soc.* 70 (1964) 566–569.
- [33] K. Gröchenig, Foundations of Time–Frequency Analysis, Birkhäuser, Boston, 2001.
- [34] R. Young, Introduction to Nonharmonic Fourier Series, Academic Press, New York, 1980.
- [35] J. Benedetto, D. Walnut, Gabor frames for  $L^2$  and related spaces, in: *Wavelets: Mathematics and Applications*, CRC Press, Boca Raton, FL, 1994, pp. 97–162.

- [36] J. Benedetto, Harmonic Analysis and Applications, in: Studies in Advanced Mathematics, CRC Press, Boca Raton, FL , 1997.
- [37] Ole Christensen . Pairs of dual Gabor frame generators with compact support and desired frequency localization . *Appl. Comput. Harmon. Anal.* 20 (2006) 403–410 .
- [38] K. Gröchenig, Foundations of Time–Frequency Analysis, Birkhäuser, Boston, 2000.
- [39] O. Christensen, An Introduction to Frames and Riesz Bases, Birkhäuser, Boston, 2003.
- [40] T. Strohmer, Approximation of dual Gabor frames, window decay and wireless communications, *Appl. Comput. Harmon. Anal.* 11 (2) (2001)243–262.
- [41] A.J.E.M. Janssen, The duality condition for Weyl–Heisenberg frames, in: H.G. Feichtinger, T. Strohmer (Eds.), *Gabor Analysis: Theory and Applications*, Birkhäuser, Boston, 1998.
- [42] A.J.E.M. Janssen, Representations of Gabor frame operators, in: Twentieth Century Harmonic Analysis—A Celebration, in: *NATO Sci. Ser.II Math. Phys. Chem.*, vol. 33, Kluwer Academic, Dordrecht, 2001, pp. 73–101.
- [43] Y. Lyubarskii, Frames in the Bargmann space of entire functions, *Adv. Soviet Math.* 11 (1992) 167–180.
- [44] K. Seip, R. Wallsten, Sampling and interpolation in the Bargmann–Fock space II, *J. Reine Angew. Math.* 429 (1992) 107–113.
- [45] H. Bölcskei, A.J.E.M. Janssen, Gabor frames, unimodularity, and window decay, *J. Fourier Anal. Appl.* 6 (3) (2000) 255–276.
- [46] I. Daubechies, S. Jaffard, J.L. Journé, A simple Wilson orthonormal basis with exponential decay, *SIAM J. Math. Anal.* 22 (1991) 554–572.
- [47] J. Benedetto, D.Walnut, Gabor frames for L<sub>2</sub> and related spaces, in: J. Benedetto,M. Frazier (Eds.), *Wavelets: Mathematics and Applications*, CRC Press, Boca Raton, FL, 1993, pp. 97–162.

- [48] I. Daubechies, A. Grossmann, Y. Meyer, Painless non orthogonal expansions, *J. Math. Phys.* 27 (1986) 1271–1283.
- [49] A.J.E.M. Janssen, Zak transforms with few zeros and the tie, in: H.G. Feichtinger, T. Strohmer (Eds.), *Advances in Gabor Analysis*, Birkhäuser, Boston, 2002.
- [50] V. Del Prete, Estimates, decay properties, and computation of the dual function for Gabor frames, *J. Fourier Anal. Appl.* 5 (6) (1999) 545–561.
- [51] K. Gröchenig, A.J.E.M. Janssen, N. Kaiblinger, G. Pfander, Note on B-splines, wavelet scaling functions, and Gabor frames, *IEEE Trans. Inform. Theory* 49 (12) (2003) 3318–3320.
- [52] C. Chui, W. He, J. Stöckler, Compactly supported tight frames and sibling frames with maximum vanishing moments, *Appl. Comput. Harmon. Anal.* 13 (3) (2002) 224–262.
- [53] I. Daubechies, B. Han, A. Ron, Z. Shen, Framelets: MRA-based constructions of wavelet frames, *Appl. Comput. Harmon. Anal.* 14 (2003) 1–46.
- [54] I. Daubechies, The wavelet transformation, time–frequency localization and signal analysis, *IEEE Trans. Inform. Theory* 36 (1990) 961–1005.
- [55] D. Walnut, *An Introduction to Wavelet Analysis*, Birkhäuser, Boston, 2001
- [56] R.S. Laugesen\*Gabor dual spline windows. Department of Mathematics, University of Illinois, Urbana, IL 61801, USA *Appl. Comput. Harmon. Anal.* 27 (2009) 180–194.
- [57] O. Christensen, *An Introduction to Frames and Riesz Bases*, Birkhäuser, Boston, 2003.
- [58] H.G. Feichtinger, T. Strohmer (Eds.), *Gabor Analysis and Algorithms*, *Appl. Numer. Harmon. Anal.*, Birkhäuser Boston, Boston, MA, 1998.
- [59] K. Gröchenig, *Foundations of Time–Frequency Analysis*, *Appl. Numer. Harmon. Anal.*, Birkhäuser Boston, Boston, MA, 2001.
- [60] O. Christensen, Pairs of dual Gabor frame generators with compact support and desired frequency localization, *Appl. Comput. Harmon. Anal.* 20 (2006) 403–410.

- [61] O. Christensen, R.Y. Kim, On dual Gabor frame pairs generated by polynomials, *J. Fourier Anal. Appl.*, in press.
- [62] O. Christensen, *Frames and Bases: An Introductory Course*, *Appl. Numer. Harmon. Anal.*, Birkhäuser Boston, Boston, MA, 2008.
- [63] A.J.E.M. Janssen, The duality condition for Weyl–Heisenberg frames, in: H.G. Feichtinger, T. Strohmer (Eds.), *Gabor Analysis and Algorithms*, in: *Appl.*
- [64] J. Lemvig, Constructing pairs of dual bandlimited framelets with desired time localization, *Adv. Comput. Math.* 30 (3) (2009) 231–247.
- [65] O. Christensen, R.Y. Kim, Pairs of explicitly given dual Gabor frames in  $L^2(\mathbb{R}^d)$ , *J. Fourier Anal. Appl.* 12 (2006) 243–255.
- [66] I. Daubechies, A. Grossmann, Y. Meyer, Painless nonorthogonal expansions, *J. Math. Phys.* 27 (1986) 1271–1283. *Numer. Harmon. Anal.*, Birkhäuser Boston, Boston, MA, 1998, pp. 33–84.
- [67] O. Christensen, R.S. Laugesen, Approximately dual frame pairs in Hilbert spaces and applications to Gabor frames, preprint,  
<http://www.math.uiuc.edu/~laugesen/>, 2008.
- [68] JAYAKUMAR RAMANATHAN? AND PANKAJ TOPIWALA. TIME-FREQUENCY LOCALIZATION VIA THE WEYL CORRESPONDENCE\*SIAM J. MATH. ANAL.Vol. 24, No. 5, pp. 1378-1393, September 1993.
- [69] D. SLEPIAN AND H. O. POLLACK, Prolate spheroidal wavejunctions, fourier analysis and uncertainty: I, *Bell Syst. Tech. J.*, 40 (1961), pp. 43-64.
- [70] H. J. LANDAU AND H. O. POLLACK, Prolate spheroidal wavefunctions, fourier analysis and uncertainty: II, III, *Bell Syst. Tech. J.*, 40,41 (1961,1962), pp. 43-64, pp.
- [71] I. DAUBECHIES, Time-frequency localization operators--a geometric phase space approach,, I, *IEEE Trans. Inform. Theory*, 34 (1988), pp. 605-612.
- [72] I. DAUBECHIES AND T. PAUL, Time-frequency localization operators--a geometric phase space approach, II, *Inverse Problems*, 4 (1988), pp. 661-680.
- [73] P. FLANDRIN, Maximal signal energy concentration in a time-frequency domain, *Proc. International Conference on Acoustics, Speech, and Signal Processing*, 1988, pp. 2176-2179.

- [74] F. HLAWATSCH, W. KOZEK, AND W. KRATTENTHALER, Time frequency subspaces and their application to time-varying filtering, Proc. International Conference on Acoustics, Speech and Signal Processing, 1990, pp. 1609-1610.
- [75] F. HLAWATSCH AND W. KOZEK, Time-frequency analysis of linear signal subspaces, Proc. International Conference on Acoustics, Speech, and Signal Processing, 1991, pp. 2045-2048.
- [76] G. B. FOLLAND, Harmonic Analysis in Phase Space, Princeton University Press, Princeton, NJ, 1989.
- [77] J. POOL, Mathematical aspects of the Weyl correspondence, *J. Math. Phys.*, 7 (1966), pp. 66-76.
- [78] A. J. E. M. JANSSEN, Positivity of weighted Wigner distributions, *SIAM J. Math. Anal.*, 12(1981), pp. 752-758.
- [79] H. WEYL, Das asymptotische Verteilungsgesetz der Eigenwerte linearer partieller Differentialgleichungen (mit einer Anwendung auf die Theorie der Hohlraumstrahlung), *Math. Ann.*, 71 (1911), pp. 441-479.
- [80] G. SZEGO, Orthogonal polynomials, Vol. 23, Amer. Math. Soc. Colloq. Publ., Providence, RI, 1959.
- [81] Y. KATZNELSON, An Introduction to Harmonic Analysis, John Wiley, New York, 1968.
- [82] Carmen Fernández, Antonio Galbis\*Compactness of time-frequency localization operators on  $L^2(\mathbb{R}^d)$  Received 2 February 2005; accepted 25 August 2005 Communicated by L. Gross available online 3 October 2005.
- [83] I. Daubechies, Time-frequency localization operators: a geometric phase space approach, *IEEE Trans. Inform. Theory* 34 (4) (1988) 605–612.
- [84] E. Cordero, K. Gröchenig, Time-frequency analysis of localization operators, *J. Funct. Anal.* 205 (2003) 107–131.
- [85] E. Cordero, K. Gröchenig, Necessary conditions for Schatten class localization operators, *PAMS* 133 (2005) 3573–3579.
- [86] P. Boggiatto, Localization operators with  $L^p$  symbols on modulation spaces, Advances in Pseudodifferential Operators, Operator Theory: Advances and Applications, Birkhäuser, Basel, Proceedings of the ISAAC Congress, 2003.

- [87] K. Gröchenig, Foundations of Time-Frequency Analysis, Birkhäuser, Basel, 2001.
- [88] A. Bényi, K. Gröchenig, C. Heil, K. Okoudjou, Modulation spaces and a class of bounded multilinear pseudodifferential operators, *J. Operator Theory*, to appear.
- [89] P. Boggiatto, E. Cordero, K. Gröchenig, Generalized anti-Wick operators with symbols in distributional Sobolev spaces, *Integral Equations Operation Theory* 48 (2004) 427–442.
- [90] R. Meise, D. Vogt, Introduction to Functional Analysis, Clarendon Press, Oxford, 1997.
- [91] L. Schwartz, Théorie des distributions, Hermann, Paris, 1978.
- [92] P. Boggiatto, Boundedness and compactness of localization operators on modulation spaces, *Quaderni del Departamento di matematica*, N. 15 (2004).
- [93] W. Ruess, Compactness and collective compactness in spaces of compact operators, *J. Math. Anal. Appl.* 84 (2) (1981) 400–417.
- [94] GITTA KUTYNIOK. BEURLING DENSITY AND SHIFT-INVARIANT WEIGHTED IRREGULAR GABOR SYSTEMS.
- [95] E. Hernández, D. Labate, and G. Weiss, A unified characterization of reproducing systems generated by a finite family, II, *J. Geom. Anal.* 12 (2002), 615–662.
- [96] A. Ron and Z. Shen, Weyl-Heisenberg frames and Riesz bases in  $L_2(\mathbb{R}^d)$ , *Duke Math. J.* 89 (1997), 237–282.
- [97] C. K. Chui, X. Shi, and J. Stöckler, Affine frames, quasi-affine frames, and their duals, *Adv. Comp. Math.* 8 (1998), 1–17.
- [98] R. Balan, P. G. Casazza, C. Heil, and Z. Landau, Density, overcompleteness, and localization of frames. Gabor systems, preprint (2005).
- [99] O. Christensen, B. Deng, and C. Heil, Density of Gabor frames, *Appl. Comput. Harmon. Anal.* 7 (1999), 292–304.
- [100] J. Ramanathan and T. Steger, Incompleteness of sparse coherent states, *Appl. Comput. Harmon. Anal.* (1995), 148–153.
- [101] H. Landau, Necessary density conditions for sampling and interpolation of certain entire functions, *Acta Math.* 117 (1967), 37–52.

- [102] I. Daubechies, Ten Lectures on Wavelets, SIAM, Philadelphia, (1992).
- [103] C. Heil and G. Kutyniok, Density of frames and Schauder bases of windowed exponentials, preprint (2005).
- [104] G. Kutyniok, Affine density, frame bounds, and the admissibility condition for wavelet frames, *Constr. Approx.*, to appear.
- [105] G. Ascensi and G. Kutyniok, Accumulative density, in “Wavelets XI” (San Diego, CA, 2005), SPIEProc., 5914, SPIE, Bellingham, WA (2005), 188–195.
- [106] K. Gröchenig, Foundations of Time-Frequency Analysis, Birkhäuser, Boston, 2001.
- [107] C. Heil, An introduction to weighted Wiener amalgams, in “Wavelets and their Applications” (Chennai, January 2002), M. Krishna, R. Radha, and S. Thangavelu, eds., Allied Publishers, New Delhi (2003), 183–216.
- [108] Jean-Pierre Gabardo 1. Weighted irregular Gabor tight frames and dual systems using windows in the Schwartz class. Received 21 June 2007; accepted 31 October 2008.
- [109] K. Gröchenig, Foundations of Time–Frequency Analysis, Birkhäuser, Basel, 2001.
- [110] G. Kutyniok, Beurling density and shift-invariant weighted irregular Gabor systems, *Sampl. Theory Signal Image Process.* 5 (2006) 163–181.
- [111] R.L. Hudson, When is the Wigner quasi-probability density non-negative?, *Rep. Math. Phys.* 6 (1974) 249–252.
- [112] J.-P. Gabardo, D. Han, Frames associated with measurable spaces, *Adv. Comput. Math.* 18 (2003) 127–147.
- [113] J.C. Lagarias, Mathematical quasicrystals and the problem of diffraction, in: Directions in Mathematical Quasicrystals, in: CRM Monogr. Ser., vol. 13, Amer. Math. Soc., Providence, RI, 2000, pp. 61–93.
- [114] J.D. Lakey, Y. Wang, On perturbations of irregular Gabor frames, in: Approximation Theory, Wavelets and Numerical Analysis, Chattanooga, TN, 2001, *J. Comput. Appl. Math.* 155 (1) (2003) 111–129.
- [115] K. Gröchenig, G. Zimmermann, Hardy’s theorem and the short-time Fourier transform of Schwartz functions, *J. London Math. Soc.* (2) 63 (2001) 205–214.

- [116] L. Schwartz, Théorie des distributions, vols. 1 and 2, Hermann, Paris, 1956.
- [117] K. Gröchenig, Y.I. Lyubarskiĭ, Gabor frames with Hermite functions, *C. R. Math. Acad. Sci. Paris* 344 (2007) 157–162.
- [118] X. Saint Raymond, An Elementary Introduction to the Theory of Pseudodifferential Operators, *Stud. Adv. Math.*, CRC Press, Boca Raton, FL, 1991.
- [119] A.J.E.M. Janssen, Gabor representation of generalized functions, *J. Math. Anal. Appl.* 83 (1981) 377–394.
- [120] K. Gröchenig, A pedestrian approach to pseudodifferential operators, in: Harmonic Analysis and Application, in Honor of John J. Benedetto, Birkhäuser Boston, Boston, MA, 2006, pp. 139–169.
- [121] Y.I. Lyubarskiĭ, Frames in the Bargmann space of entire functions, in: Entire and Subharmonic Functions, in: *Adv. Soviet Math.*, vol. 11, Amer. Math. Soc., Providence, RI, 1992, pp. 167–180.
- [122] K. Seip, Density theorems for sampling and interpolation in the Bargmann–Fock space. I, *J. Reine Angew. Math.* 429 (1992) 91–106.
- [123] K. Seip, R. Wallstén, Density theorems for sampling and interpolation in the Bargmann–Fock space. II, *J. Reine Angew. Math.* 429 (1992) 107–113.
- [124] L. Hörmander, The Analysis of Linear Partial Differential Operators I. Distribution Theory and Fourier Analysis, Springer-Verlag, Berlin, 1983.
- [125] A. Ron, Z. Shen, Frames and stable bases for shift-invariant subspaces of  $L^2(\mathbb{R}^d)$ , *Canad. J. Math.* 47 (1995) 1051–1094.
- [126] J. Wexler, S. Raz, Discrete Gabor expansions, *Signal. Process.* 21 (1990) 207–220.
- [127] H.G. Feichtinger, W. Kozek, Quantization of TF lattice-invariant operators on elementary LCS groups, in: *Gabor Analysis and Algorithms*, Birkhäuser Boston, Boston, MA, 1998, pp. 233–266.
- [128] R. Balan, P. Casazza, C. Heil, Z. Landau, Density, overcompleteness, and localization of frames. II. Gabor systems, *J. Fourier Anal. Appl.* 12 (2006) 309–344.
- [129] O. Christensen, B. Deng, C. Heil, Density of Gabor frames, *Appl. Comput. Harmon. Anal.* 7 (1999) 292–304.

- [130] J. Ramanathan, T. Steger, Incompleteness of sparse coherent states, *Appl. Comput. Harmon. Anal.* 2 (1995) 148–153.
- [131] H.G. Feichtinger, K. Gröchenig, Banach spaces related to integrable group representations and their atomic decompositions. I, *J. Funct. Anal.* 86 (1989) 307–340
- [132] H.G. Feichtinger, Wenchang Sun, Sufficient conditions for irregular Gabor frames, *Adv. Comput. Math.* 26 (2007) 403–430.
- [133] Ole Christensen · Rae Young Kim. On Dual Gabor Frame Pairs Generated by Polynomials. 8 January 2008 / Revised: 14 October 2008 / Published online: 27 March 2009 © Birkhäuser Boston 2009.
- [134] Janssen, A.J.E.M.: The duality condition for Weyl-Heisenberg frames. In: Feichtinger, H.G., Strohmer, T. (eds.) *Gabor Analysis: Theory and Applications*. Birkhäuser, Boston (1998)
- [135] Ron, A., Shen, Z.: Frames and stable bases for shift-invariant subspaces of  $L^2(\mathbb{R}^d)$ . *Can. J. Math.* 47(5), 1051–1094 (1995)
- [136] Christensen, O.: *Frames and Bases. An Introductory Course*. Birkhäuser, Basel (2007)
- [137] Heil, C., Walnut, D.: Continuous and discrete wavelet transforms. *SIAM Rev.* 31, 628–666 (1989)
- [138] Rudin, W.: *Real and Complex Analysis*, 3rd edn. McGraw-Hill, New York (1986)
- [139] Strang, G., Nguyen, T.: *Wavelets and Filter Banks*. Cambridge Press, Wellesley (1997)
- [140] Chui, C.K.: *An Introduction to Wavelets*. Academic Press, Boston (1992)
- [141] Keinert, F.: *Wavelets and Multiwavelets*. Chapman & Hall/CRC, Boca Raton (2004)
- [142] Christensen, O.: Pairs of dual Gabor frames with compact support and desired frequency localization. *Appl. Comput. Harmon. Anal.* 20, 403–410 (2006)
- [143] Ole Christensen, Hong Oh Kim, Rae Young Kim, \* Gabor windows supported on  $[-1, 1]$  and compactly supported dual windows  $\star$ . *Appl. Comput. Harmon. Anal.* 28 (2010) 89–103

- [144] O. Christensen, *Frames and Bases. An Introductory Course*, Birkhäuser, 2007.
- [145] K. Gröchenig, *Foundations of Time–Frequency Analysis*, Birkhäuser, Boston, MA, 2000.
- [146] C. Heil, D. Walnut, Continuous and discrete wavelet transforms, *SIAM Rev.* 31 (1989) 628–666.
- [147] H. Bölcskei, A.J.E.M. Janssen, Gabor frames, unimodularity, and window decay, *J. Fourier Anal. Appl.* 6 (3) (2000) 255–276.
- [148] R.S. Laugesen, Gabor dual spline windows, *Appl. Comput. Harmon. Anal.* (2009) 180–194.
- [149] O. Christensen, R.Y. Kim, On dual Gabor frame pairs generated by polynomials, *J. Fourier Anal. Appl.* (2009), in press.
- [150] O. Christensen, Pairs of dual Gabor frames with compact support and desired frequency localization, *Appl. Comput. Harmon. Anal.* 20 (2006) 403–410.
- [151] A. Ron, Z. Shen, Frames and stable bases for shift-invariant subspaces of  $L^2(\mathbb{R}^d)$ , *Canad. J. Math.* 47 (5) (1995) 1051–1094.
- [152] A. Ron, Z. Shen, Weyl–Heisenberg frames and Riesz bases in  $L^2(\mathbb{R}^d)$ , *Duke Math. J.* (89) (1997) 237–282
- [153] A.J.E.M. Janssen, The duality condition for Weyl–Heisenberg frames, in: H.G. Feichtinger, T. Strohmer (Eds.), *Gabor Analysis: Theory and Applications*, Birkhäuser, Boston, MA, 1998.
- [154] Elena Corderoa and Karlheinz Grochenig\*. Time–Frequency analysis of localization operators *Journal of Functional Analysis* 205 (2003) 107–131.
- [155] I. Daubechies, Time–frequency localization operators: a geometric phase space approach, *IEEE Trans. Inform. Theory* 34 (4) (1988) 605–612.
- [156] J. Ramanathan, P. Topiwala, Time–frequency localization via the Weyl correspondence, *SIAM J.Math. Anal.* 24 (5) (1993) 1378–1393.
- [157] H.G. Feichtinger, K. Nowak, A first survey of Gabor multipliers, in: H.G. Feichtinger, T. Strohmer (Eds.), *Advances in Gabor Analysis*, Birkhäuser, Boston, 2002.

- [158] M.W. Wong, Localization operators, Seoul National University Research Institute of Mathematics Global Analysis Research Center, Seoul, 1999.
- [159] M.W. Wong, Wavelets Transforms and Localization Operators, Vol. 136 of Operator Theory Advances and Applications, Birkhäuser, Basel, 2002
- [160] F.A. Berezin, Wick and anti-Wick symbols of operators, Mat. Sb. (N.S.) 86 (128) (1971) 578–610.
- [161] M.A. Shubin, Pseudodifferential Operators and Spectral Theory, 2nd Edition, Springer-Verlag, Berlin, 2001 Translated from the 1978 Russian original by Stig I. Andersson.
- [162] A. Cōrdoba, C. Fefferman, Wave packets and Fourier integral operators, Comm. Partial Differential Equations 3 (11) (1978) 979–1005.
- [163] I. Daubechies, On the distributions corresponding to bounded operators in the Weyl quantization, Comm. Math. Phys. 75 (3) (1980) 229–238.
- [164] H.G. Feichtinger, Un espace de Banach de distributions tempérées sur les groupes localement compacts abéliens, C. R. Acad. Sci. Paris Sé r. A-B 290 (17) (1980) A791–A794.
- [165] G.B. Folland, Harmonic Analysis in Phase Space, Princeton University Press, Princeton, NJ, 1989.
- [166] K. Grochenig, Foundations of Time–Frequency Analysis, Birkhäuser Boston, Boston, MA, 2001.
- [167] H.G. Feichtinger, On a new Segal algebra, Monatsh. Math. 92 (4) (1981) 269–289.
- [168] P. Boggiatto, E. Cordero, Anti-Wick quantization of tempered distributions, in: H.G.W. Begehr, R.P. Gilbert, M.W. Wong (Eds.), Advances in Analysis, World Scientific, 2003, pp. 655–662.
- [169] M.W. Wong, Localization operators on the Weyl–Heisenberg group, in: Geometry, Analysis and Applications, Varanasi, 2000, World Scientific Publishing, River Edge, NJ, 2001, pp. 303–314.
- [170] P. Boggiatto, E. Cordero, K. Grochenig, Generalized Anti–Wick operators with symbols in distributional Sobolev spaces, preprint, 2002.

- [171] K. Grochenig, C. Heil, Modulation spaces and pseudodifferential operators, *Integral Equations Operator Theory* 34 (4) (1999) 439–457.
- [172] K. Grochenig, G. Zimmermann, Hardy’s theorem and the short-time Fourier transform of Schwartz functions, *J. London Math. Soc.* 63 (2001) 205–214.
- [173] P. Jaming, Principe d’incertitude qualitatif et reconstruction de phase pour la transformée de Wigner, *C. R. Acad. Sci. Paris Sér. I Math.* 327 (1998) 249–254.
- [174] A.J.E.M. Janssen, Proof of a conjecture on the supports of Wigner distributions, *J. Fourier Anal. Appl.* 4 (6) (1998) 723–726.
- [175] E. Galperin, K. Grochenig, Uncertainty principles as embeddings of modulation spaces, *J. Math. Anal. Appl.* 274 (1) (2002) 181–202.
- [176] J. Bergh, J. Löfström, *Interpolation Spaces, An Introduction*, Springer, Berlin, 1976 Grundlehren der Mathematischen Wissenschaften, No. 223.
- [177] E.M. Stein, *Singular Integrals and Differentiability Properties of Functions*, Princeton University Press, Princeton, NJ, 1970 Princeton Mathematical Series, No. 30.
- [178] H.G. Feichtinger, Modulation spaces on locally compact abelian groups, Technical report, University of Vienna, 1983.
- [179] H.G. Feichtinger, Banach convolution algebras of Wiener type, in: *Functions, Series, Operators*, Vols. I, II, Budapest, 1980, North-Holland, Amsterdam, 1983, pp. 509–524.
- [180] H.G. Feichtinger, Generalized amalgams, with applications to Fourier transform, *Canad. J. Math.* 42 (3) (1990) 395–409.
- [181] H.G. Feichtinger, G. Zimmermann, A Banach space of test functions for Gabor analysis, in: *Gabor Analysis and Algorithms*, Birkhäuser Boston Inc., Boston, MA, 1998, pp. 123–170.
- [182] J.J.F. Fournier, J. Stewart, Amalgams of  $L^p$  and  $l^q$ ; *Bull. Amer. Math. Soc. (N.S.)* 13 (1) (1985) 1–21.
- [183] J. Toft, Modulation spaces and pseudodifferential operators, Preprint, 2002
- [184] J. SJÖSTRAND, An algebra of pseudodifferential operators, *Math. Res. Lett.* 1 (2) (1994) 185–192.

- [185] K. Grochenig, An uncertainty principle related to the Poisson summation formula, *Stud. Math.* 121 (1) (1996) 87–104.
- [186] A.-P. Calderon, R. Vaillancourt, On the boundedness of pseudo-differential operators, *J. Math. Soc. Japan* 23 (1971) 374–378.
- [187] L. Hörmander, The Weyl calculus of pseudodifferential operators, *Comm. Pure Appl. Math.* 32 (3) (1979) 360–444.
- [188] F. Treves, *Topological Vector Spaces, Distributions and Kernels*, Academic Press, New York, 1967.
- [189] H.G. Feichtinger, K. Grochenig, Banach spaces related to integrable group representations and their atomic decompositions. II, *Monatsh. Math.* 108 (2–3) (1989) 129–148.
- [190] F.F. Bonsall, Decompositions of functions as sums of elementary functions, *Quart. J. Math. Oxford Ser. (2)* 37 (146) (1986) 129–136.
- [191] MONIKA D'ORFLER, HANS G. FEICHTINGER AND KARLHEINZ GRÖCHENIG. SEQUENCE OF TIME-FREQUENCY PARTITIONS FOR THE GELFAND TRIPLE  $(S_0, L^2, S'_0)$  2000 Mathematics Subject Classification. 94A12, 47B38, 47G30.
- [192] F. De Mari, H. G. Feichtinger, and K. Nowak. Uniform eigenvalue estimates for time-frequency localization operators. *J. London Math. Soc.* (2), 65(3):720–732, 2002.
- [193] I. Daubechies. The wavelet transform, time-frequency localization and signal analysis. *IEEE Trans. Inform. Theory*, 36(5):961–1005, 1990.
- [194] J. Ramanathan and P. Topiwala. Time-frequency localization via the Weyl correspondence. *SIAM J. Math. Anal.*, 24(5):1378–1393, 1993.
- [195] M. W. Wong. Localization operators on the Weyl-Heisenberg group. In *Geometry, analysis and applications* (Varanasi, 2000), pages 303–314. World Sci. Publishing, River Edge, NJ, 2001.
- [196] F. A. Berezin. Wick and anti-Wick symbols of operators. *Mat. Sb. (N.S.)*, 86(128):578–610, 1971.
- [197] A. Córdoba and C. Fefferman. Wave packets and Fourier integral operators. *Comm. Partial Differential Equations*, 3(11):979–1005, 1978.

- [198] I. M. Gel'fand and N. Ya. Vilenkin. Generalized functions. Vol. 4. Academic Press [Harcourt Brace Jovanovich Publishers], New York, 1964 [1977]. Applications of harmonic analysis. Translated from the Russian by Amiel Feinstein.
- [199] I. Daubechies. Ten lectures on wavelets. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, 1992.
- [200] Karlheinz Gröchenig. Foundations of time-frequency analysis. Birkhäuser Boston Inc., Boston, MA, 2001.
- [201] H. G. Feichtinger and T. Strohmer, editors. Gabor analysis and algorithms: theory and applications. Birkhäuser Boston, Boston, MA, 1998.
- [202] H. G. Feichtinger. On a new Segal algebra. *Monatsh. Math.*, 92(4):269–289, 1981.
- [203] H.G. Feichtinger and G. Zimmermann. A Banach space of test functions for Gabor analysis. In H.G. Feichtinger and T. Strohmer, editors, *Gabor Analysis and Algorithms: Theory and Applications*, pages 123–170.
- [204] H. G. Feichtinger and W. Kozek. Quantization of TF lattice-invariant operators on elementary LCA groups. In *Gabor analysis and algorithms*, pages 233–266. Birkhäuser Boston, Boston, MA, 1998.
- [205] A. J. E. M. Janssen. The Zak transform: a signal transform for sampled time-continuous signals. *Philips J.Res.*, 43(1):23–69, 1988.
- [206] J.J. Benedetto, C. Heil, and D.F. Walnut. Gabor systems and the Balian-Low theorem. In *Gabor analysis and algorithms*, pages 85–122. Birkhäuser Boston, Boston, MA, 1998.
- [207] H. G. Feichtinger and K. Gröchenig. Gabor frames and time-frequency analysis of distributions. *J. Functional Anal.*, 146(2):464–495, 1997.
- [208] Elena Cordero and Karlheinz Gröchenig. Time-frequency analysis of localization operators. *J. Funct. Anal.*, 205(1):107–131, 2003.
- [209] Paolo Boggiatto and Elena Cordero. Anti-Wick quantization with symbols in  $L^p$  spaces. *Proc. Amer. Math. Soc.*, 130(9):2679–2685 (electronic), 2002.
- [210] Hans G. Feichtinger and Krzysztof Nowak. A first survey of Gabor multipliers. In *Advances in Gabor analysis*, *Appl. Numer. Harmon. Anal.*, pages 99–128. Birkhäuser Boston, Boston, MA, 2003. Birkhäuser, Boston, 1998. Chap. 3.

- [211] Lars Hörmander. The analysis of linear partial differential operators. III, volume 274 of Grundlehren der Mathematischen Wissenschaften [Fundamental Principles of Mathematical Sciences]. Springer-Verlag, Berlin, 1985.
- Pseudodifferential operators.
- [212] J. E. Moyal. Quantum mechanics as a statistical theory. Proc. Cambridge Philos. Soc., 45:99–124, 1949.
- [213] Monika Dörfler, Karlheinz Gröchenig\* Time-frequency partitions and characterizations of modulation spaces with localization operators  $\star$ . Received 7 December 2009; accepted 21 December 2010.
- [214] K. Brandenburg, M. Kahrs (Eds.), Applications of Digital Signal Processing to Audio and Acoustics, Engineering and Computer Science/Kluwer Academic Publishers, 2003.
- [215] S.J. Godsill, P.J.W. Rayner, Digital Audio Restoration, Springer, 1998.
- [216] I. Daubechies, Time-frequency localization operators: a geometric phase space approach, IEEE Trans. Inform. Theory 34 (4) (1988) 605–612.
- [217] P. Jaming, Principe d’incertitude qualitatif et reconstruction de phase pour la transformée de Wigner, C. R. Acad. Sci. Paris Sér. I Math. 327 (1998) 249–254.
- [218] A.J.E.M. Janssen, Proof of a conjecture on the supports of Wigner distributions, J. Fourier Anal. Appl. 4 (6) (1998) 723–726.
- [219] E. Wilczock, Zur Funktionalanalysis der Wavelet- und Gabortransformation, thesis, TU München, 1998.
- [220] E. Cordero, K. Gröchenig, Time-frequency analysis of localization operators, J. Funct. Anal. 205 (1) (2003) 107–131.
- [221] J. Toft, Continuity properties for modulation spaces, with applications to pseudo-differential calculus. I, J. Funct. Anal. 207 (2) (2004) 399–429.
- [222] M.-W. Wong, Wavelet Transforms and Localization Operators, Oper. Theory Adv. Appl., vol. 136, Birkhäuser, Basel, 2002.
- [223] J.-M. Bony, J.-Y. Chemin, Functional spaces associated with the Weyl–Hörmander calculus (Espaces fonctionnels associés au calcul de Weyl–Hörmander), Bull. Soc. Math. France 122 (1) (1994) 77–118

- [224] J.-M. Bony, N. Lerner, Quantification asymptotique et microlocalisations d'ordre supérieur. I, Ann. Sci. École Norm. Sup. (4) 22 (3) (1989) 377–433.
- [225] K. Gröchenig, J. Toft, Isomorphism properties of Toeplitz operators and pseudo-differential operators between modulation spaces, *J. Anal. Math.*, in press.
- [226] W. Sun, G-frames and g-Riesz bases, *J. Math. Anal. Appl.* 322 (October 2006) 437–452.
- [227] M. Dörfler, H.G. Feichtinger, K. Gröchenig, Time-frequency partitions for the Gelfand triple ( $S_0, L^2, S_0'$ ), *Math.Scand.* 98 (1) (2006) 81–96.
- [228] H.G. Feichtinger, K. Gröchenig, Gabor wavelets and the Heisenberg group: Gabor expansions and short time fourier transform from the group theoretical point of view, in: C.K. Chui (Ed.), *Wavelets: A Tutorial in Theory and Applications*, Academic Press, Boston, MA, 1992, pp. 359–398.
- [229] F. Luef, Projective modules over non-commutative tori are multi-window Gabor frames for modulation spaces, *J. Funct. Anal.* 257 (6) (2009) 1921–1946.
- [230] K. Gröchenig, *Foundations of Time-Frequency Analysis*, *Appl. Numer. Harmon. Anal.*, Birkhäuser, Boston, 2001.
- [231] K. Gröchenig, Weight functions in time-frequency analysis, in: L. Rodino, M.-W. Wong, et al. (Eds.), *Pseudodifferential Operators: Partial Differential Equations and Time-Frequency Analysis*, in: *Fields Inst. Commun.*, vol. 23, 2007, pp. 343–366.
- [232] C. Heil, An introduction to weighted Wiener amalgams, in: M. Krishna, R. Radha, S. Thangavelu (Eds.), *Wavelets and Their Applications*, Chennai, January 2002, Allied Publishers, 2003, pp. 183–216.
- [233] H.G. Feichtinger, K. Gröchenig, Gabor frames and time-frequency analysis of distributions, *J. Funct. Anal.* 146 (2) (1997) 464–495.
- [234] K. Gröchenig, M. Leinert, Wiener's lemma for twisted convolution and Gabor frames, *J. Amer. Math. Soc.* 17 (2004) 1–18.
- [235] K. Gröchenig, Gabor frames without inequalities, *Int. Math. Res. Not.* (2007), 2007, Article ID rnm111, 21 pp.
- [236] I. Daubechies, The wavelet transform, time-frequency localization and signal analysis, *IEEE Trans. Inform. Theory* 36 (5) (1990) 961–1005.

- [337] J. Ramanathan, P. Topiwala, Time-frequency localization via the Weyl correspondence, *SIAM J. Math. Anal.* 24 (5) (1993) 1378–1393.
- [238] P. Louizou, *Speech Enhancement: Theory and Practice*, CRC Press, 2007.
- [239] C. Roads, *The Computer Music Tutorial*, MIT Press, 1998.
- [240] F.A. Berezin, Wick and anti-Wick symbols of operators, *Mat. Sb. (N.S.)* 86 (128) (1971) 578–610.
- [241] A. Córdoba, C. Fefferman, Wave packets and Fourier integral operators, *Comm. Partial Differential Equations* 3 (11) (1978) 979–1005.
- [242] N. Lerner, The Wick calculus of pseudo-differential operators and some of its applications, *Cubo Mat. Educ.* 5 (1) (2003) 213–236.
- [243] E. Cordero, K. Gröchenig, L. Rodino, Localization operators and time-frequency analysis, in: N.M. Chong, et al.(Eds.), *Harmonic, Wavelet and p-Adic Analysis*, World Scient. Publ., 2007, pp. 83–109, 2006.
- [244] C. Fernandez, A. Galbis, Compactness of time-frequency localization operators on  $L^2(\mathbb{R})$ , *J. Funct. Anal.* 233 (2) (2006) 335–350.
- [245] R.C. Busby, H.A. Smith, Product-convolution operators and mixed-norm spaces, *Trans. Amer. Math. Soc.* 263 (2) (1981) 309–341.
- [246] P. Boggiatto, E. Cordero, Anti-Wick quantization with symbols in  $L^p$  spaces, *Proc. Amer.Math. Soc.* 130 (9) (2002) 2679–2685 (electronic).
- [247] H.G. Feichtinger, K. Nowak, A first survey of Gabor multipliers, in: *Advances in Gabor Analysis*, in: *Appl. Numer. Harmon. Anal.*, Birkhäuser Boston, Boston, MA, 2003, pp. 99–128.
- [248] H.G. Feichtinger, K. Gröchenig, Banach spaces related to integrable group representations and their atomic decompositions.I, *J. Funct. Anal.* 86 (2) (1989) 307–340.
- [249] H.G. Feichtinger, K. Gröchenig, Banach spaces related to integrable group representations and their atomic decompositions.II, *Monatsh. Math.* 108 (2–3) (1989) 129–148.
- [250] A.J.E.M. Janssen, Duality and biorthogonality for Weyl–Heisenberg frames, *J. Fourier Anal. Appl.* 1 (4) (1995) 403–436.

[251] M. Fornasier, K. Gröchenig, Intrinsic localization of frames, *Constr. Approx.* 22 (3) (2005) 395–415.

[252] Shawgy Hussein and Amna Mohamed Ali , Gabor windows and dual systems with characterizations of modulation spaces of localization operators , Ph.D thesis, Sudan University of Science and Technology, sudan 2016.